BALANCING CARBON IMPACT AND NATURAL LIGHTING IN URBAN RESIDENTIAL HOUSING PROJECT: SHANGHAI, CHINA

A D.ARCH. PROJECT SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAIʻI AT MĀNOA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF ARCHITECTURE

MAY 2018

By

Ling Li

DArch Committee:

Clark Llewellyn
Yiru Huang
William Chapman

Keywords: residential housing, natural lighting design, carbon emission

ABSTRACT

Under the circumstance of rapid development, problems like energy consumption, carbon emission and quality of living issues in China have emerged in recent years. Housing has demonstrated tremendous potential to play a major role in the reduction of carbon emission, to gain a balance between reducing carbon emission and meeting increasing demand. Good natural lighting is irreplaceable in improving the quality of housing and meeting needs of the residents. Thus, it is necessary and insightful to evaluate natural lighting of housing from the perspective of carbon emission reduction.

The research approach includes five aspects: literature review, software simulation, questionnaire survey, empirical research and case study. This research aims to identify the role and significance of natural lighting of housing has on carbon emission, to establish a connection between them and to reveal their relationships to improve the overall quality of housing and realize energy-saving principles and carbon emission.

This dissertation will prove that appropriate natural lighting of housing can achieve a balance in natural lighting quality, energy consumption and carbon emission. It is promising that this research can provide references and ideas for the governments, designers and developers to impact future decisions that will help to create high quality housing and reduce carbon emission at the same time.

Key Words: residential housing, natural lighting design, carbon emission

ACKNOWLEDGEMENTS

At this point, an academic journey will eventually come to an end. Time flies, the time spent in University of Hawai‘i pursuing doctorate degree is short and somehow long. Campus career is about to be completed. In full of dreams for the future, I cannot help feeling the satisfaction and a little sadness.

First of all, I would like to say thank you to prof. Yiru Huang, my admirable supervisor in Tongji University, prof. Clark E. Llewellyn, my respectful supervisor in University of Hawai‘i, Hongtao Zhou, Bin Hu and other professors in Global Track program. Your knowledge, guidance, kindness and patience are the most precious treasures which help me finish my study in this dual-degree program successfully.

In addition to the beloved teacher, I would like to express my gratitude to my parents. I cannot grow so well without their love and care. You are the first mentor in my life; you are the one who always give me confidence and support no matter what I am trying to do. I have learned so much from you, my most lovable people in the world, there is no such a word that I can use to fully express my feeling towards to you. It is you who made me who I am and I will never let you down.

At the same time, how can I forget GT 5 students who worked together in the studio, coming all the way along - Yuqing Han, Yating Fan, Juncheng Shen, Mark Lombawa, Joern Vallesteros as well as Duo Xu, Shun Zeng and Lingkun Jia that helped me with my thesis. Thank you for so many memories that we have shared together. Also I want to say thank you to the others who gave me guidance and help during my study period both in Tongji University and University of Hawaiʻi, thank you for spending the most beautiful time in my life so far.

Life is also about learning for a lifelong time. The end of one journey is also another start of the new one. I hope we all can always keep the initial desire in mind and achieve our goals in the future.

Finally, I wish the very best to my beloved teacher, prof. Yiru Huang and prof. Clark E. Llewellyn, wish you always laugh in daily life and everything goes fine in the future. Wish my parents can always be happy after their retirement. Wish all my classmates and friends can realize their dreams in the near future. And the last but not the least, once again I want to express my sincere gratitude to all who are always there to support me and help me. Thank you!

In University of Hawaiʻi, March 2018

CONTENTS

CHAPTER 1 INTRODUCTION

1.1 Research Background

With the further transformation of China's development, energy saving and carbon emission reduction has gradually become the key word since twenty-first Century. On the one hand, with the rapid progress of science and technology, innovative materials and the promotion of the concept of green ecology, low carbon emission has become hot topics and research frontiers in various industries. On the other hand, with the continuous development of the new era and the improvement of people's living standard, the residential building, the type most closely related to people's daily life, its evaluation standards are also rising. However, from the traditional point of view, energy saving, carbon emission reduction and pursuit of quality seem to be at opposite ends of the balance. The key point to solve this problem is to chase the perfect balance between them by analyzing and evaluating their pros and cons.

From the perspective of energy consumption and carbon emission, it is affected by many factors. And design often plays a decisive role as a pre-decision phase in the construction industry chain and becomes an important part of materialization of buildings and daily use in the whole period. The result can be much better if we take the concept of energy saving and carbon emission reduction into consideration of the early design phase of residential buildings and use it as an important design basis and standard for evaluating.

From the perspective of improving quality of residential buildings, including lighting condition, it is not only the desire driven by the architect, but also the common pursuit of every party related to. Thus, how to control the design process of residential building through rational thinking becomes the key to solve the problem.

1.1.1 The Status Quo of Residential Natural Lighting Design in China

The development of residential housing has gone through many stages, in recent decades, with the establishment and implementation of both national and local housing related energy saving standards promulgated and other mandatory codes. And residential design conforms to reflect functional practicability and economic efficiency, the main design trend. However, at the same time, architects do not just stick to this thought; they are desired to create residential building with higher quality more than just meeting the basic standards for residential building. Design ideas are updated constantly, advocating better user experience and more human care aspects.

These design concepts, advocating of living quality, user experience and human care, make residential buildings, cold artificial products, become more “humanized”, also make the residential buildings truly become “home” instead of just “house”, “the harbor of the inner feelings”. But it is undeniable that the residential buildings in the city are losing the connection to the nature because they have to be built in a higher density way in order to facing the lack of land. This situation makes the needs for dialogues with nature elements much more urgent for the residential buildings. As we all know, natural light is one of the inexhaustible energy. Apart from that, transparent windows and other building components that can let light come in can also broaden the horizons and make the boundary between inner and outer spaces less rigid. All those advantages make natural lighting become one of the main concerns for design of residential building in recent china. According to the present situation of our country, urban residential lighting design has two potential problems to be solved. One is that a considerable part of the residential lighting design only aims at meeting the basic codes, while the other is that some emphasis too much on user experience without weighing rational analysis to guide the design. Both of these aspects make the actual situation after the completion of the residential buildings may not meet the design expectations and original design vision, and bring some problems related to experience and energy consumption, which needs to be further studied.

1.1.2 The Significance of Natural lighting in Residential Building

Natural lighting, which is not only an important design element in residential environment, but also an irreplaceable part in the existing residential evaluation system, includes arrangement, distance control for buildings and so on in residential district planning level as well as self-occlusion, window forms, units design in residential building design level.

The relationship between the natural light and the residential building has always been inseparable since housing was created. The natural light, one of the few natural elements that could interact with buildings, gives much more feelings or sensations to users and gives more meaning or significance to residential buildings. First of all, natural lighting ensures and improves the functionality of the housing. Human activities depend largely on vision as a medium, and appropriate lighting just provides an appropriate environment for the normal use of users. At the same time, natural lighting not only meets the functionality of the basis need, but also provides a visual comfort that cannot be places by artificial lighting, which includes quality and quantity as two aspects. In terms of quality, the visual efficacy curve of natural lighting is generally better than that of artificial light in every environment setting (Figure 1.1), and compared with the latter, the natural light is harder to cause visual fatigue and discomfort; and in terms of quantity, the numerical of natural lighting in most cases can meet the normal activities required for illumination due to its lighting source are sunlight and skylight. In addition, natural light can often offer a certain degree of pleasure of interaction with nature intimacy to users as psychological experience; apart from that, it also can bring some psychological sense of stability and a sense of warmth to users because of its warm color and make the house become a place with warm atmosphere. Thus, natural lighting has an irreplaceable functional significance for housing.

Figure 1.1 Visual efficacy curves of natural light and artificial light

Source: Architecture Physics

1.1.3 Context Switching from Energy Saving to Carbon Emission Reduction

The time when China began to introduce energy saving as a design index dates back to the late 90s. The energy-saving design standards widely used in the building construction industry for sustainable design were largely based on the codes focused on saving electricity. While the carbon dioxide emissions, a representative of the greenhouse gas has become a new sustainable index under the current circumstance. And the concept of carbon emission reduction is permeated into different industry stage of almost every subject nowadays. From the perspective of dimension, carbon emission is a comprehensive index, which covers the whole life cycle of buildings, it transfers the view of simply saving energy consumption to reduce greenhouse gas emissions in a comprehensive perspective. It is an inevitable trend for the evaluation of sustainable development of architecture and other subjects.

1.2 Purpose and Significance of This Research

The main purpose of this research is to study the relationship between lighting design and carbon emission of residential housing. The former research and past experience have shown that the good residential lighting condition and energy saving in hot summer and cold winter area are two sides of one coin, they cannot be achieved both, which means improving natural lighting condition will bring more energy consumption in daily use. Nevertheless, study on the outcomes of different design methods of natural lighting from both the perspective of carbon emission reduction and lighting quality may bring a new understanding of how exactly they affect each other and design guidelines about how to achieve goal of pursuing sustainable and high quality in the future design.

1.3 Research Methods

The major methods adopted in this research include relevant theory research and literature review, software simulation, questionnaire survey, empirical analysis based on case studies and so on.

The related theory research and literature review method is mainly through the study of former related researches, aiming to understand the development of residential lighting design and both domestic and foreign research status, to help form the structure and important ideas of this research; software simulation is applied to simulate hypothetical lighting and carbon emission situations according to different settings of variables by using following softwares developed in China, which are PKPM-Daylight and PKPM-PBECA; questionnaire survey method is combined with the real residential buildings chosen to be studied in this research, used to gather the responses and related information from the residents of targeted residential housing projects; empirical analysis is based on case studies to analysis and conclude their key points of design on lighting quality and sustainable aspects as important supporting materials.

The application of the methods mentioned above is not completely independent, they have connections to each other and they work together to make this research a complete and comprehensive study on this chosen topic.

CHAPTER 2 THEORETICAL RESEARCH AND LITERATURE REVIEW

2.1 Related Studies on Natural Lighting Design of Residential Housing

The study of residential lighting design in China approximately began after the worldwide energy crisis in the last century, accompanied by the general awakening of the design consciousness in the architectural design industry. Here are some examples of related studies showing the whole research background of this field.

By summing up the lighting design of residential housing in western European countries, Sun Ming (1987) proposed that the demand and subjective evaluation of the residents are more important than the lighting factor of single horizontal surface. He also emphasized that residential lighting design should take the requirements of vision and landscape, sunshine and lighting condition these three aspects into consideration. Song Zhonglie (1992) put forward his idea that the lighting design should use dynamic sky conditions for calculation. Entering the new century, with the new residential lighting specifications and the implementation of energy saving norms and codes, as well as the application of computer-aided simulation technology, the vision and depth of studies on residential lighting design are enhanced by a great margin. Li Defu and Zhu Minmin (2000) applied computer simulation technology to study the natural daylighting design of residential buildings in Beijing and concluded the impact ratio of residential balconies is

30%. Ran Maoyu (2000) used the lighting coefficient as the main lighting evaluation index, explored the minimum window area and the window-wall ratio in residential buildings and proposed that lighting design of residential building should be controlled with the minimum window area. Li Baofeng (2004) argued that the "changeable" part of the architectural façade/skin has the potential to meet the totally different requirements of both winter and summer. It can solve the energy-saving and lighting problem of residential buildings in hot-summer and cold-winter zones. The possibility of applying passive solar energy in hot summer and cold winter area in China were discussed based on "changeable design strategy" concept. Jia Dongming (2006) proposed some ideas including changing the window-wall ratio to mandatory requirements; using single room as a unit rather than an average unit of the room when calculating the window-wall ratio; bay window should not be used in the room facing north; low bay windows and full windows should not be applied. Jiao Yanghui (2008) systematically studied and concluded the development of energy-saving windows in the hot-summer and cold-winter area. In his research, Zhang Ji (2009) discussed the ways and tactics for the active and passive utilization of natural light in residential areas along the Yangtze River region, the central part of China. Through detailed investigation and study on the utilization of sunlight in houses in four major cities along the Yangtze River, the study focused on four aspects including single unit graphic design, the use of natural light and balance between the lighting, heat insulation and keeping warmth to explore residential design methods in depth. Zhang Bin (2010) studied how to integrate different design requirements into the initial design stage to make a comprehensive consideration so as to achieve optimal design. Through the use of the "monthly average illuminance" index, the effect of window form on indoor lighting coefficient distribution and energy consumption of building equipment was studied by software simulation method. The concept of "lighting energy efficiency" was raised as a new index to evaluate the condition of lighting and energy saving. Xie Hao (2011) discussed some issues that should be paid attention to in natural lighting design of modern residential buildings, including indoor light environment distribution, lighting techniques and related requirements. Bian Weifeng (2015) used Ecotect software to conduct a passive optimization based on software analysis of a residential district in Nanjing.

Compared to domestic studies, foreign researches focus more on the qualitative analysis of the physical environment and users. Koster (2007) studied the basic principles of lighting, the relevant physical laws, the main technical means of operation and their functions based on that period. And he also discussed their economic factors. Peter (2014) pointed out that households had a subjective tendency toward the effects of residential lighting; different natural lighting will bring different orientation and sensory experiences; it was difficult to specify single and physical parameter indicators to reflect the lighting conditions; proposed residential design should become a subtle, a complex state in his own research.

Existing relevant researches include the research methods of software simulation, case analysis and empirical research to discuss the energy-saving, experience of user and aesthetic considerations of residential lighting design, which have been relatively mature. However, there are few studies focused on residential lighting design and dynamic assessment from the perspective of carbon emission reduction, so this research would be an implement and make some contribution in this field.

2.2 Theories and Standards of Carbon Emission

In the field of carbon emission, many foreign developed countries have formed a variety of mature systems based on many years of theoretical and engineering practices and explorations. The well-known green building evaluation system is a representative example. These existing research frameworks provide a strong foundation and support to this study. Among them, the most credible evaluation system in the world includes Life Cycle Assessment (LCA), Ecological Footprint and LEED in United States.

China started its own research on carbon emission area just recently. In 2002, China promulgated the Environmental Management-Life Cycle Assessment-Life Cycle Impact Assessment (GB/T 24020-1999). This national standard was a translation version of the international standard ISO 14140. In the field of building construction, our country adopted the Low Carbon Building Method as the main standard to evaluate the carbon emissions. After then, in 2014, China has formally implemented the first carbon emissions calculation standard-Standard for Measuring, Accounting and Reporting of

Carbon Emission from Buildings (CECS 374-2014), which combined the ISO international standards and took actual situation of construction industry characteristics in China into consideration. It was based on the LCA system and provided a theoretical basis for calculating our building construction data.

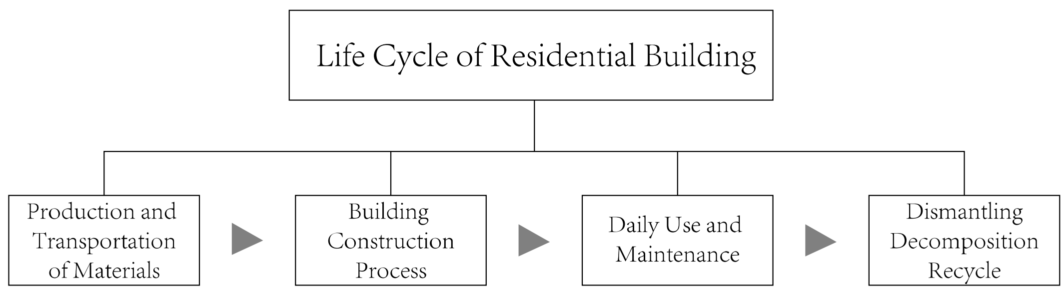


Figure 2.1 LCA of residential building

Source: Author

One focus of this research is the changes of carbon emissions in the whole life cycle caused by residential lighting design strategies.

The database of the calculation process of carbon emission in this research mainly includes two parts. The first one is the database of Eco Calculator for Residential Assemblies, based on LCA, which is developed by Athena Sustainable Materials Institute. Its data includes amount of GWP (Global Warming Potential) values, presented as CO_2 equivalent figures of related materials and components from materialization, to construction, demolition and recycling stages. The other one is based on the energy-saving design software PKPM-PBECA developed by Chinese Academy of Construction Science and Technology to simulate the energy consumption of main building equipment (heating and cooling equipment) during the use stage and construction period, then converted into CO_2 equivalent numbers according to energy standards in China.

Table 2.1 GWP value of main greenhouse gases

Type	CO_2	CO	CH4	N_2O	PFCs	HFCs	PFCs
GWP	1	2	27	296	5700	11700	22200

Data Source: Intergovernmental Panel on Climate Change

CHAPTER 3 CARBON IMPACT OF NATURAL LIGHTING DESIGN ON RESIDENTIAL BUILDING

3.1 Research Scope and Object

3.1.1 Research Scope

As described in the previous section, this chapter will focus on the carbon impact of residential lighting design on residential buildings during their materialization, demolition and use phases according to the whole life cycle building evaluation system.

The carbon impact of lighting design on residential buildings, as its literal meaning, is the carbon emission changes of the building design caused by different residential considerations of natural daylighting on design level, such as setting different shapes and sizes of windows, setting different heights of window sills and other related variables.

According to the Standard for Measuring, Accounting and Reporting of Carbon Emission from Buildings (CECS 374-2014), mentioned in the previous chapter as a main basis of this research, the main carbon emission units in the whole life cycle of residential buildings can refer to Table 3.1 as listed below.

Table 3.1 Main carbon emission units of residential buildings

Phase	Carbon Emission Units
Production	Material, components and equipment use for production of main structure, envelope and fulfillment.
Construction	Transportation of material, components and equipment; operation of equipment.
Use and Maintenance	Operation of building systems; maintenance of material, components and equipment.
Demolishing and Recycling	Operation of demolishing equipment; transportation of construction waste; recycling of the structure, envelope, and fulfillment.

Source: CECS 374-2014

The table above covers almost all carbon emission units over the entire life cycle of a residential housing. The complexity of the data is beyond the scope of this research. Simplifying the study is a compromise to keep the research scientific without losing focus on the research. Given the former related studies, this research will be focused on the most relevant aspects related to residential lighting carbon emissions unit to conduct the following study in depth as listed below: (1) production phase of building materials, construction phase, demolishing and recycling phase; (2) operating phase of the equipment system. Different considerations of residential lighting design will change the building shape, the use of materials and performance of the building envelope and affect the overall energy consumption. These two aspects of the study are interrelated and constitute the carbon impact of residential lighting design on residential life cycle (operating time is counted as 50 years). The basic calculation equation is listed as following formula 3.1.

$$\Delta E = \Delta E_M + \Delta E_U \tag{3.1}$$

ΔE is the change of carbon emission ($kgCO_2eq$) in whole life cycle due to residential lighting related variables;

ΔE_M is the change of carbon emission ($kgCO_2eq$) caused by relevant lighting design variables of production, construction, demolishing and recycling phase of residential building;

ΔE_U is the change of carbon emission ($kgCO_2eq$) in the operation phase of residential building due to residential lighting design variables.

3.1.2 Research Object

Since entering the new century, with the improvement of living standard and purchasing will, the quality of residential buildings has increasingly become a focus of consumers. As a central city in the Yangtze River Delta region of China, Shanghai is also a representative city in hot-summer and cold-winter zone. Urban housing in Shanghai has always been at the forefront of China. Based on the data collection and investigation, this study screened the typical residential buildings in Shanghai which have been already built as the research objects. The selected objects, sharing common in detailed drawings, energy-saving calculation manuals, documents and all in a high degree completion compared with design documents, being suitable as research objects for further software simulation, calculation and analysis. The basic information of the residential unit chosen is showed in the following Table 3.2.

Table 3.2 Basic information of the chosen residential building in Shanghai

Location	Shanghai（31°N，121°E）
Zone	Hot-summer and cold-winter
Construction Year	2009
Orientation	South
Structure	Shear wall structure
Building Shape Coefficient	0.39
Building Area	3442.17 m^2
Building Volume	10451.11 m^2
Surface area	4119.31 m^2
Floor	12
Building Height	37.35 m
Exterior Wall Type (from Outside to Inside)	Concrete block, 2 coat stucco over porous surface, R5 XPS continuous insulation
Window Type	Aluminum operable low-e double glazing
Window/Wall Ratio	East 0.05；South 0.35；West 0.05；North 0.35
Running Time	24 hours/d
Energy Consumption of Simulation（Summer）	21.65 kwh/m^2
Energy Consumption of Simulation（Winter）	36.23 kwh/m^2
Energy Consumption of Simulation（Year）	57.89 kwh/m^2

Source: Author

3.2 Research on Physical Environment and Related Norms

3.2.1 Outdoor Thermal Environment and Thermal Design Zoning

Residential buildings, the initial artificial structure that human beings invented to resist infiltration from nature, the relationship with the natural environment have been updating since it was ever born. In particular, how to adapt to and utilize the environment where buildings live is becoming an important starting point of design under the circumstance of emphasizing regional and sustainable ideas nowadays.

The outdoor thermal environment, also called outdoor climate, refers to the general terms of all thermal and wet physical factors acting on the building envelope where the building is located, which is the primary factor affecting the indoor environment.[1]

The outdoor thermal environment of buildings is primarily related to the thermal insulation in summer and winter, and the heating and cooling energy consumption used to maintain a comfortable indoor thermal environment. As we all know, China has a vast territory. In the Code for Thermal Design of Civil Buildings (GB50176-93), 5 thermal climate zones are divided according to the temperatures of the coldest month and the hottest month as the main indicators; including extremely cold, cold, hot-summer and cold-winter, hot-summer and warm-winter and mild zone (Figure 3). On this basis, the corresponding design requirements for each climatic zone were put forward. The selected research object was completed in Shanghai, according to the norms mentioned above, the

[1] Liu Xiaotu. Building Physics [M]. Beijing: China Building Industry Press, 2000

area is located in the hot-summer and cold-winter zone. This zone has characters for being very cold in winter and being hot in summer. It is a typical complex climate with different conditions.

Figure 3.1 Thermal design zoning map for building in China

Source: Code for Thermal Design of Civil Buildings (GB 50176-93)

3.2.2 Natural Light Climate Zoning

There are many factors that affect the outdoor light climate. In order to apply the standardized light climate data in the lighting design, the lighting design and calculation are widely based on the dominant sky condition of the region or the "CIE general sky condition."[2] The difference of natural light conditions in different regions of our country is quite significant. Therefore, similar to the thermal zoning, the light climate zoning is

[2] Ibid

put forward according to the total annual average illumination value (Figure3.2). On this basis, the climate index K and the reference outdoor illumination Value for design are listed as below (Table 3.3).

Table 3.3 Light climate coefficient K

Light Climate Zone	I	II	III	IV	V
K Value	0.85	0.90	1.00	1.10	1.20
Design Value	18000	16500	15000	13500	12000

Source: Lighting Design Standard of Building (GB 50033-2013)

Figure 3.2 Light climate zone map of China

Source: Lighting Design Standard of Building (GB 50033-2013)

3.2.3 The Relevant Norms Involved in This Research

In order to conduct the simulation in a scientific way, the reference norms of this study chosen based on the construction time of the object as following, includes Standard for Measuring, Accounting and Reporting of Carbon Emission from Buildings (CECS 374-2014), Code for Thermal Design of Civil Buildings (GB 50176-93), Lighting Design Standard of Buildings (GB 50033-2013), Energy-saving Design Standard for Residential Buildings in Hot summer and Cold-winter Zone (JGJ134-2001) and other relevant standards.

Energy-saving Design Standard for Residential Buildings in Hot summer and Cold-winter Zone (JGJ134-2001) specifies the basic calculation parameters for indoor thermal environment. The design temperature for heating in winter should be 18℃ for all days and the heating period is from December 1 to February 28 in the next year; air conditioning design temperature in summer should be 26℃ for all day long, with air conditioning period from June 15 to August 31. In addition, the detailed limits and dynamic evaluating indexes are listed due to a series of parameters with impact on energy consumption, such as the building shape coefficient of residential buildings, the window/wall ratio on different orientations, the heat transfer coefficient of building envelopes and so on.

The purpose of lighting is to get a comfortable indoor light environment, in the case of natural lighting, indoor illumination fluctuations with the changes in outdoor illumination, so our country and many other countries apply the relative value of the lighting coefficient of the building for lighting design. The lighting coefficient is calculated as formula 3.2 showing:

$$C = (E_N/E_W) \times 100\% \quad (3.2)$$

C represents the lighting coefficient (%);

E_N represents the illuminance (lx) produced at a given point in a given plane inside the room under sky diffuse light;

E_W represents the illuminance (lx) produced at a given point in a given plane outside the room by the sky diffuse light at the same place as E_N.

The subsequent lighting evaluation will be combined with the average value of the lighting coefficient and its distribution area as the basis for judging the lighting conditions and qualities, which constitute the following calculation and research evaluation system and will be described in detail later on.

3.3 Carbon Emission Changes Caused by Residential Natural Lighting Design in Use Phase

3.3.1 Introduction of Software Used for Simulation

Software such as Energy Plus, PKPM-PBECA, DeST, DOE-2, PKPM-Daylight, Ecotect, Daysim and Radiance can be used in the current field of building energy consumption calculation and lighting design simulation for design analysis. Among them, the PKPM-PBECA has an advantage among them because it is independently developed for China, rooted in local context and can support more than 80 national and local energy-saving design standards. Moreover, it is also developed based on the AutoCAD platform with excellent compatibility. Thus, it is chosen as the simulation software for energy consumption in this study. For the PKPM-Daylight, it shares the same calculating unit as Radiance developed in United States, uses Monte Carlo algorithm based on the optimization of the reverse tracking algorithm, the working principle is to subdivide a room into the same size of the grid, take a fictitious plane with a height of 0.75 meters from the indoor ground as a calculation plane. With the iterative illumination calculation, detailed lighting coefficient distribution illustration can be drawn for each room as well as the glare calculation. Another important part that it shares the same model with PKPM-PBECA, simplifying the modeling process, and eliminating the potential errors caused by shifting between different software models. Last but not the least, it also supports for the latest lighting design specifications and norms of China. Therefore, it is selected as the simulation software for lighting design analysis of this study.

3.3.2 Process of Software Simulation and Analysis

In order to systematically study the impact of residential lighting design on residential carbon emissions, the simulation process will be applied with the control variable method based on the 3D model of the selected reference residential building. After the simulation process, the energy consumption and lighting condition of each circumstance will be simulated and analyzed correspondingly to summarize the basic laws from the simulation results from different settings of parameters.

Software simulation phase includes several parts as described below:

(1) Building a base model as reference

The reference model is built based on the completed residential building which is selected as the research object in previous section 3.1.3 according to its construction drawings. Modeling operation process is as follows: Open each AutoCAD drawings of the selected residential building (Figure 3.3), import the tables of windows and doors, according to the total plane to select the compass direction, classify them with different categories - structural columns, walls, doors, windows and other building components according to their functions in the drawings. Then assign them to the component attributes of PKPM-PBECA model respectively, convert them into the PKPM-PBECA model as corresponding typical floor plans of the residential building to complete the model and finally, set the properties of the wall, balcony and room type (Figure 3.4). Afterwards, copy the different typical plans and assemble them into a complete residential building, check and compare the 3D model with the drawings to make sure it is correct. (Figure 3.5). After completing the above steps, enter the material editor (Figure 3.6). Set the components with right materials according to the construction drawings, to reflect the real situation to the maximum.

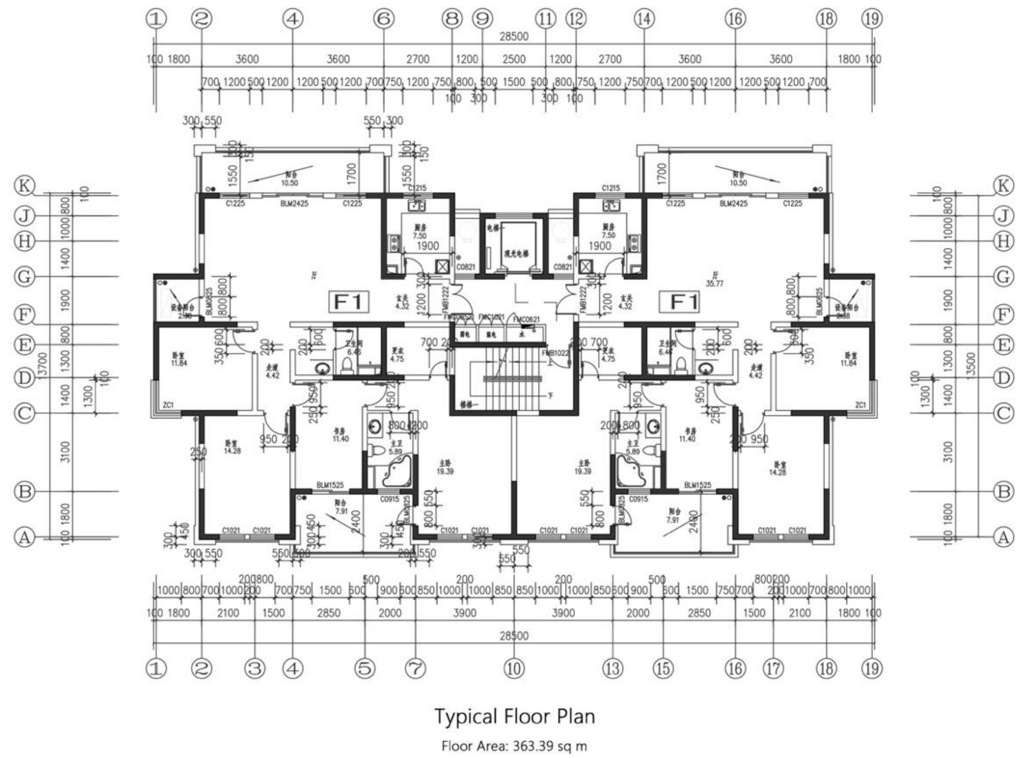


Figure 3.3 The typical plan of the selected residential building

Source: TJAD

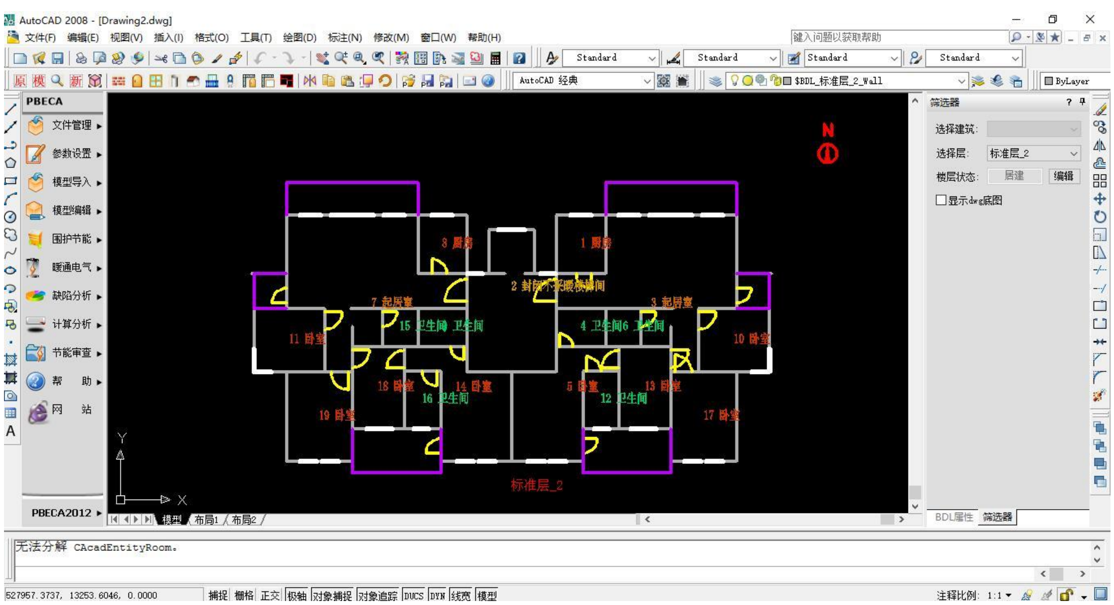


Figure 3.4 PKPM-PBECA interface display: typical floor modeling

Source: Author

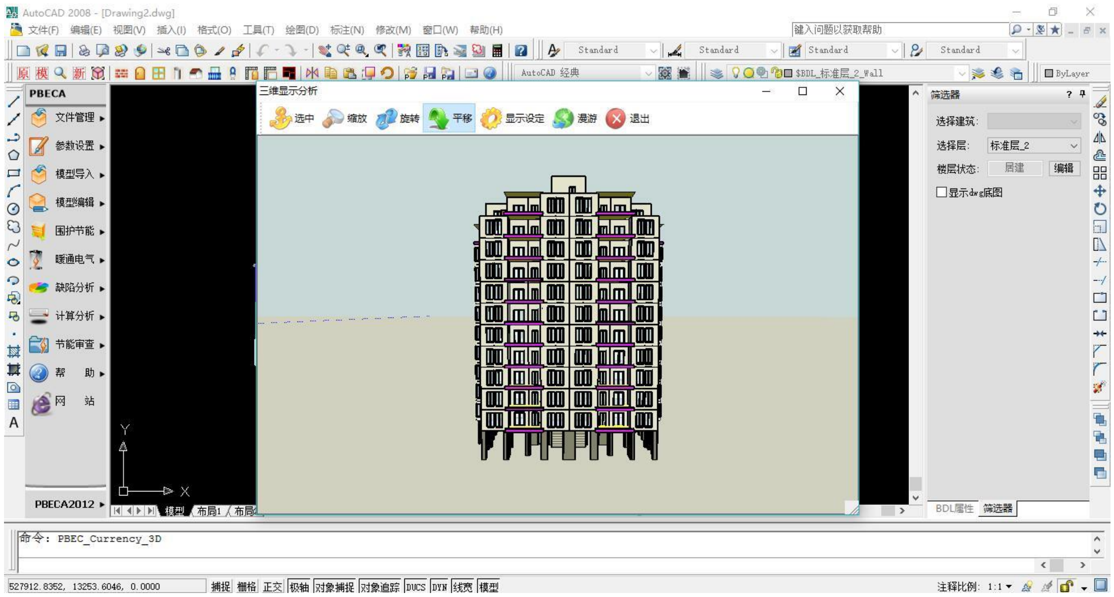


Figure 3.5 PKPM-PBECA interface display: 3D view of model

Source: Author

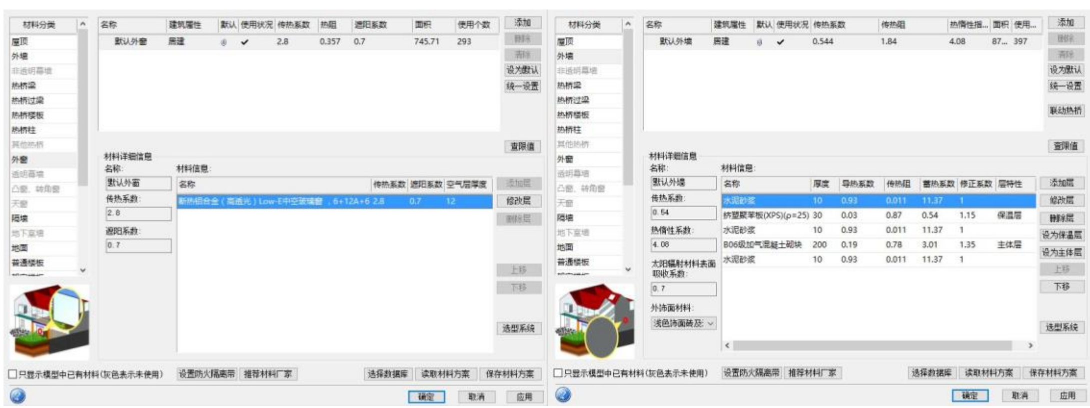


Figure 3.6 PKPM-PBECA interface display: material editing

Source: Author

Software PKPM-Daylight can share the same model with PKPM-PBECA, so the base model is saved into Daylight for further simulation of lighting condition after the completion in PKPM-PBECA. The principle of modeling is quite the same as mentioned above, the interior surface material editing, lighting configuration and glare calculation are further completed according to the construction drawings and specifications (Table 3.4, Figure 3.7-Figure 3.9).

Table 3.4 Settings of lighting related material parameters of simulation model

Components	Material	Interior Reflectance	Visible Light Transmittance
Interior Wall	Cement mortar plaster surface	0.32	——
Interior Ceiling	Cement mortar plaster surface	0.32	——
Interior Floor	Cement mortar plaster surface	0.32	——
Exterior Window	6+12A+6	——	0.72

Source: Author

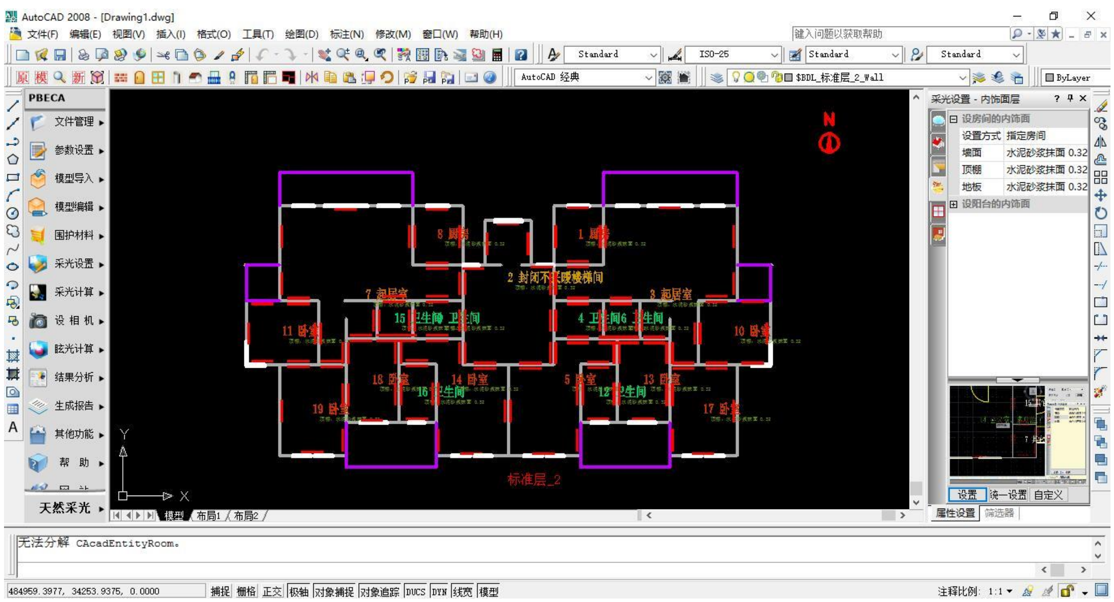


Figure 3.7 Daylight interface display: typical plan

Source: Author

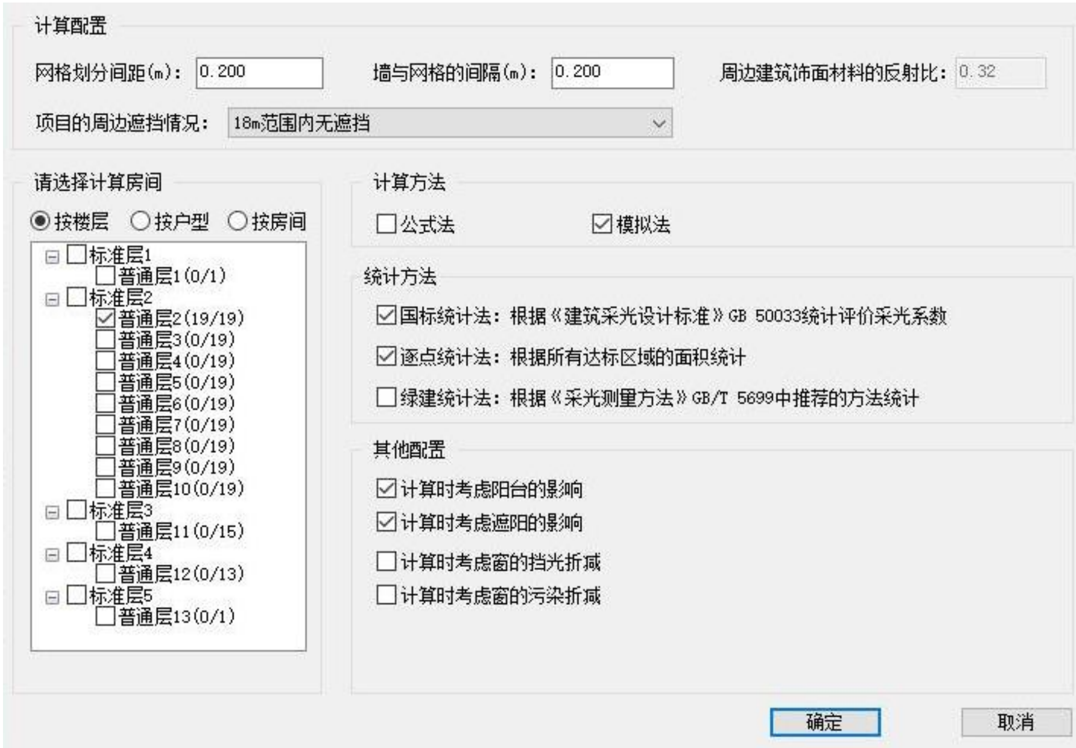


Figure 3.8 Daylight interface display: configuration

Source: Author

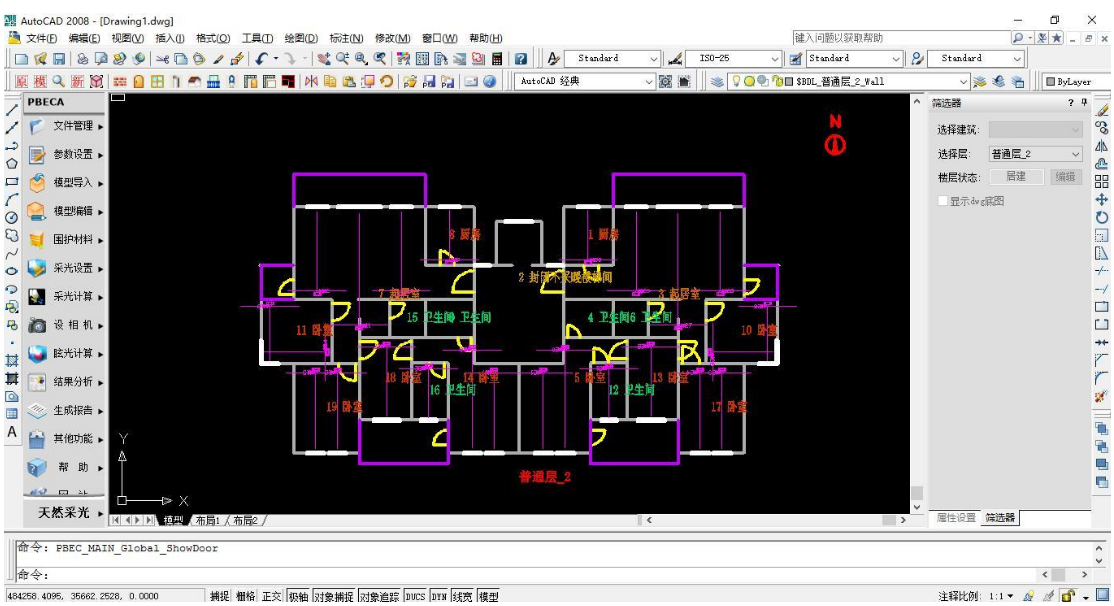


Figure 3.9 Daylight interface display: settings of glare calculation

Source: Author

(2) Settings of Relevant Parameters and Variables

Choosing the related parameters and variables for this research is a key step that can directly affect the simulation results. Learning from the comprehensive literature review in the previous chapter, the main factors that will make an impact of residential lighting condition and energy consumption probably include the following aspects: height of windowsill, window/wall ratio (window area), the physical properties of the window itself (material transmissivity, shading coefficient, thermal performance and other related parameters), shading conditions and others. The first two aspects among the variables listed above, the windowsill height and window/wall ratio, which are both important indicators of design phase and controlling indexes in codes and norms. Thus, this research will focus on these two aspects as main variables. Due to the fact that windows with rectangle shapes are mostly used in residential buildings, the area of them is decided by their heights and widths, which is a composite variable. In order to fully study the relationship between energy consumption and lighting condition, the variable - area is further subdivided into two variables, height and width in the following simulation, calculation and analysis.

After the base models are built, they are saved as new files for parameter settings with all the other original conditions staying the same. The window height is set as 0.90m in order to make the parameter setting of windowsill heights cover a bigger range while not being unreasonable. On the basis of this, a series sub-models of windowsill heights from 0.00m to 2.10m at an interval of 0.30m are built, and to make the comparisons, choosing the model with height of windowsill for 0.00m as the reference model in this subdivision. As for parameter settings of window area, in order to make the window area cover from 0-100% of each direction of the building, the height of windowsill is set as 0.00m in unity, while the height and width of the window is adjusted separately to reflect the effect of the window area with another set as the maximum value of the model when studying either one (the window height is set as floor height when study the window width, vice versa). Therefore, like we mentioned above, simulation models with window/wall ratio from 0% to 100% at an interval of 10% are built and the model with 0% window/wall ratio is chosen as a reference model to make comparisons to study the impact and the relationship of lighting variables and energy consumption.

(3) Simulation of Energy Consumption and Natural Lighting

The simulation of energy consumption and natural lighting are conducted respectively based on the models mentioned above. The simulation of energy consumption is divided into two parts in the PKPM-PBECA, one is the calculation of the required indexes, and the other is the calculation of the comprehensive indexes. Simulation section of lighting is conveyed by national standard simulation method, including the diagram of light distribution and the glare calculation. After the completion of the simulation and calculation, the software will automatically generate the corresponding reports of each model. The outcome of the reports will be expanded in detail in the following parts.

3.3.3 Simulation of Natural Lighting and Energy Consumption in Use Phase

(1) Simulation results of east windowsill height

Table 3.5 The relationship between simulated energy consumption in use phase and east windowsill height (KWh/m^2)

Window/Wall Ratio：East 0.30 South 0.30 West 0.30 North 0.30 Window Height 0.90m Others Parameters as Reference Model								
Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
Annual Cooling Energy Increment	0.000	-0.008	-0.016	-0.021	-0.023	-0.014	-0.004	0.000
Annual Heating Energy Increment	0.000	0.009	0.018	0.027	0.034	0.031	0.027	0.024
Annual Total Energy Increment	0.000	0.001	0.002	0.006	0.011	0.017	0.023	0.024

Source: Author

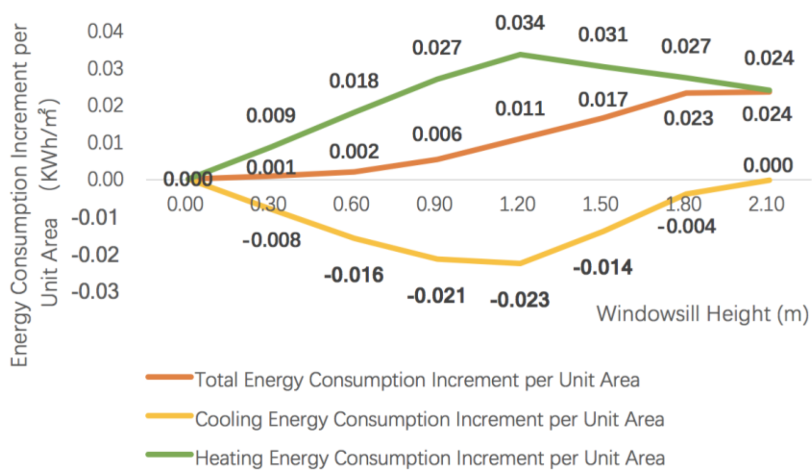
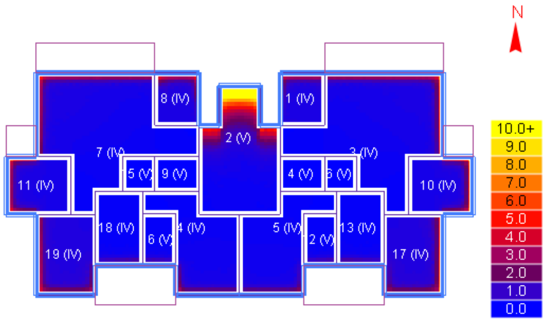


Figure 3.10 Relationship between simulated energy consumption in use phase and east windowsill height

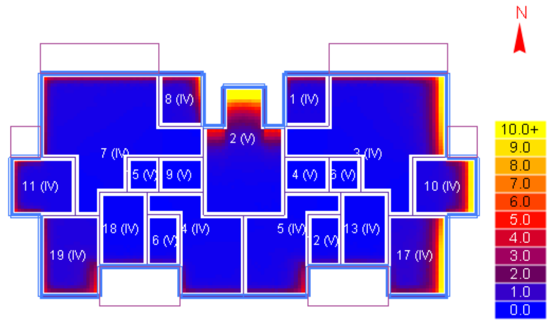
Source: Author

Table 3.5 and Figure 3.10 show the energy consumption changes in use phase caused by east windowsill height. The values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a windowsill height of 0.00m. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the energy consumption of heating increases with the increment of the east windowsill height while the other parameters staying the same; the cooling energy consumption decreases with the increase of the east windowsill height, reaches its peak when east windowsill height is at 1.20m and then goes up; the change of total energy consumption per unit area still shows a positive correlation with the increase of the east windowsill height, the maximum incremental value is 0.024KWh/m^2 when the windowsill height is 2.10m. Given the magnitude of the incremental value is little, it can be considered that the east windowsill height has little influence on the energy consumption in use phase of residential building.

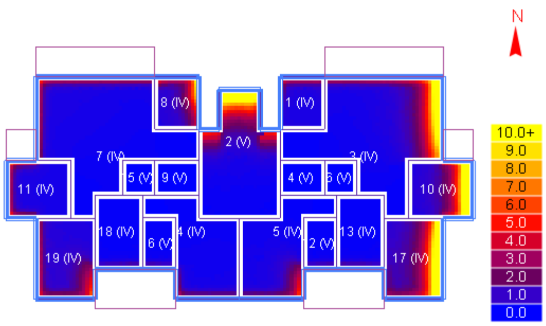
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different east windowsill heights were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.11).



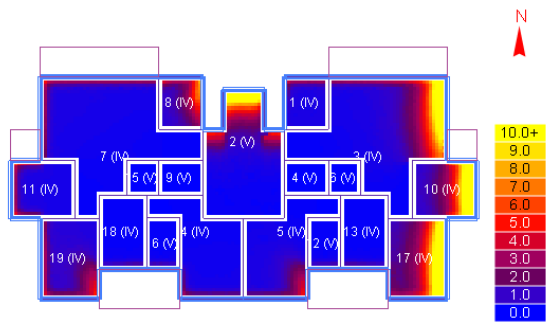
(a) east windowsill height 0.00m



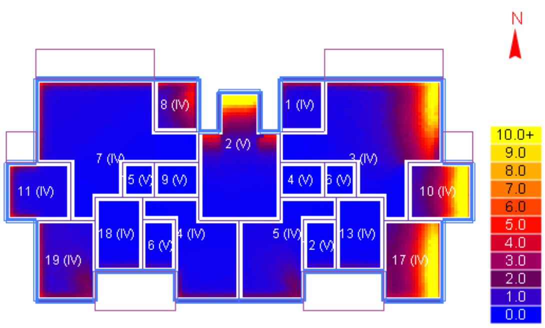
(b) east windowsill height 0.30m



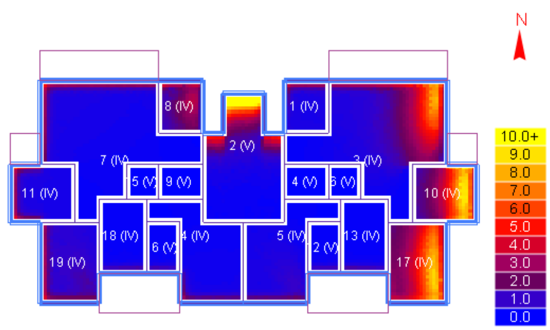
(c) east windowsill height 0.60m



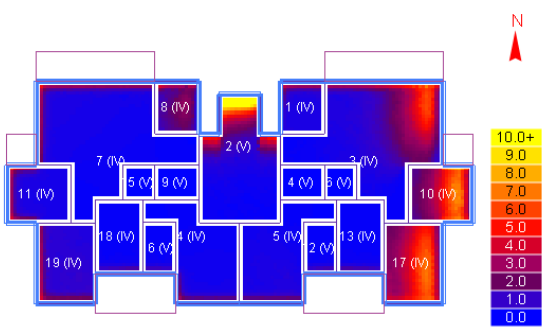
(d) east windowsill height 0.90m



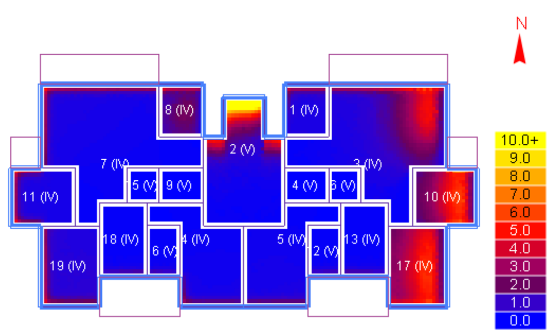
(e) east windowsill height 1.20m



(f) east windowsill height 1.50m



(g) east windowsill height 1.80m



(h) east windowsill height 2.10m

Figure 3.11 Lighting coefficient distribution of east rooms

Source: Author

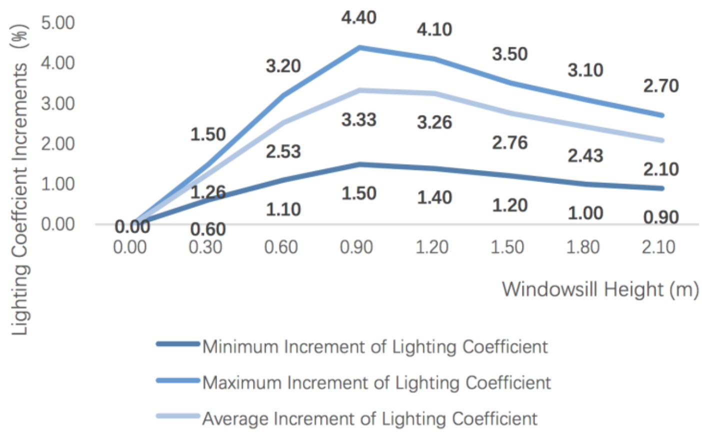


Figure 3.12 Lighting coefficient increments of east rooms

caused by east windowsill heights

Source: Author

Combining with the lighting coefficient distribution of east rooms and the data from lighting simulation report, the average lighting coefficient of each room in the east rooms is obtained. As shown in Figure 3.12, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a windowsill height of 0.00m. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the east windowsill height, reaches the peak and the inflection point when it is 0.90m; then decreases with the increment of the east windowsill height; according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is different even when the lighting coefficient value are nearly the same, with one windowsill height at 0.60m while another windowsill height at 1.80m; with the windowsill height increasing, the lighting coefficient of the area near windowsill gradually decreases and the lighting coefficient of the area away from windowsill increases. In summary, the average lighting coefficient of the room shows an increasing trend when windowsill height increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the east windowsill height and reaches the turning point of 0.90m, then goes down from the peak.

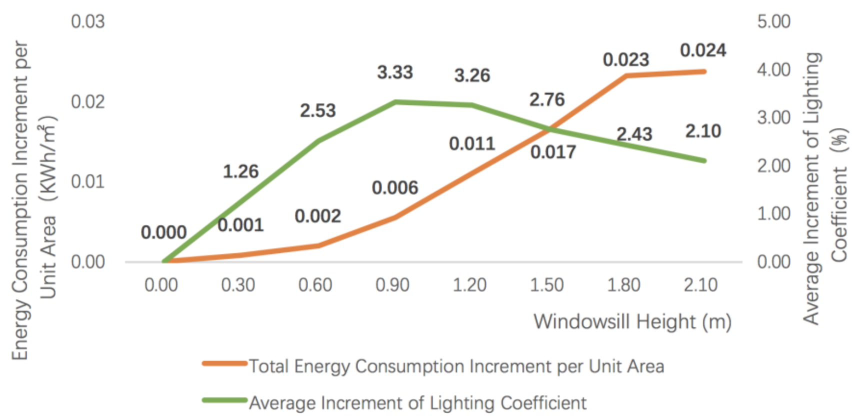


Figure 3.13 Increments of lighting coefficient and total energy consumption caused by east windowsill heights

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.13), which shows the relationships between the east windowsill height, the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. Although the lighting coefficient begins to go down after the peak point when east windowsill height is at 0.90m, the overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way. However, in the meantime, the magnitude of energy consumption increment is so little that can be ignored in our decision-making phase.

(2) Simulation results of south windowsill height

Table 3.6 The relationship between simulated energy consumption in use phase and south windowsill height (KWh/m^2)

Window/Wall Ratio：East 0.30 South 0.30 West 0.30 North 0.30 Window Height 0.90m Others Parameters as Reference Model								
Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
Annual Cooling Energy Increment	0.000	0.003	0.016	0.019	0.023	0.027	0.033	0.036
Annual Heating Energy Increment	0.000	0.006	-0.004	-0.004	-0.006	-0.009	-0.015	-0.013
Annual Total Energy Increment	0.000	0.008	0.012	0.015	0.017	0.018	0.018	0.023

Source: Author

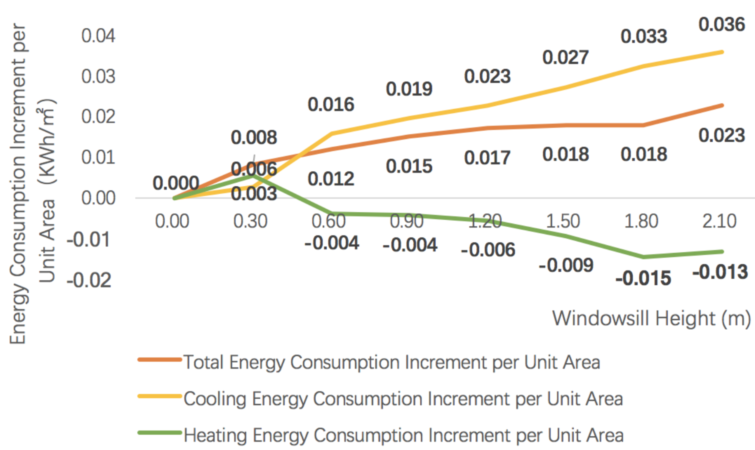
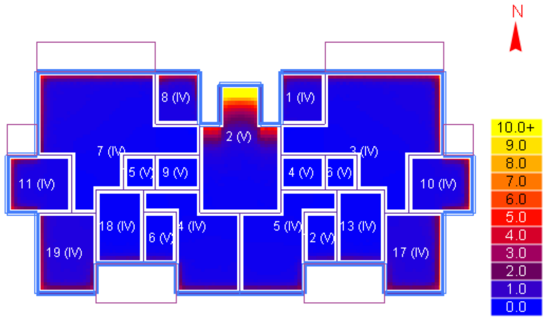


Figure 3.14 Relationship between simulated energy consumption in use phase and south windowsill height

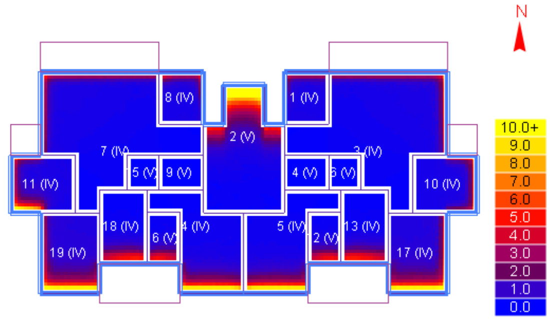
Source: Author

Table 3.6 and Figure 3.14 show the energy consumption changes in use phase caused by south windowsill height. The values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a windowsill height of 0.00m. Contrary to (1), it can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the energy consumption of cooling increases with the increment of the south windowsill height while the other parameters staying the same; the heating energy consumption decreases with the increase of the south windowsill height, reaches its peak when south windowsill height is at 1.80m and then goes up; however, similarly with (1), the change of total energy consumption per unit area still shows a positive correlation with the increase of the south windowsill height, the maximum incremental value is 0.023KWh/m^2 when the windowsill height is 2.10m. Given the magnitude of the incremental value is little, it can be considered that the south windowsill height has little influence on the energy consumption in use phase of residential building.

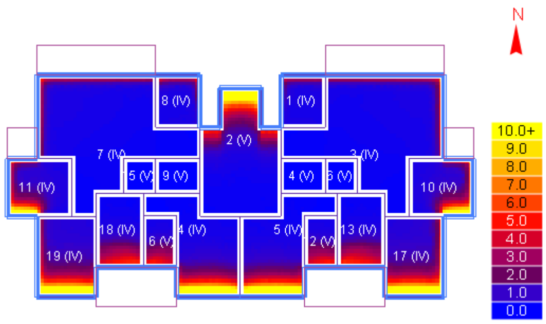
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different south windowsill heights were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.15).



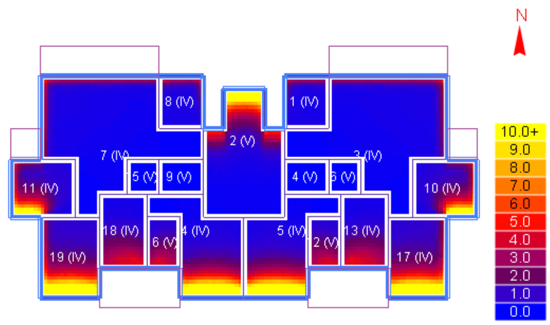
(a) south windowsill height 0.00m



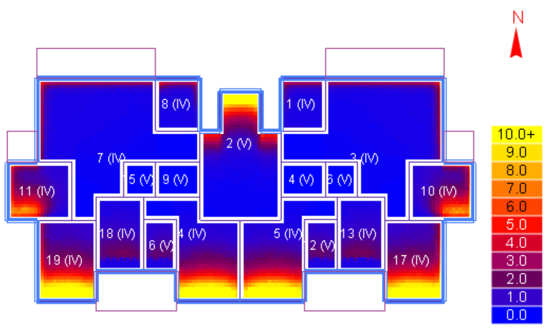
(b) south windowsill height 0.30m



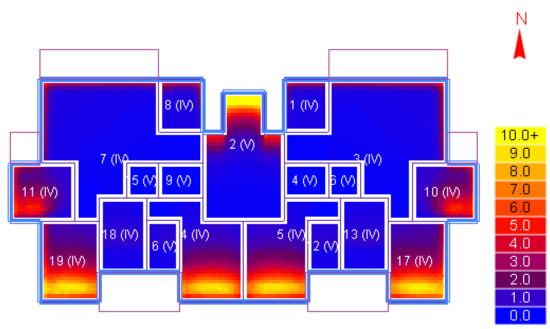
(c) south windowsill height 0.60m



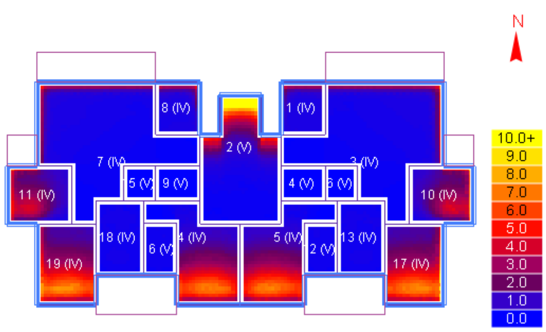
(d) south windowsill height 0.90m



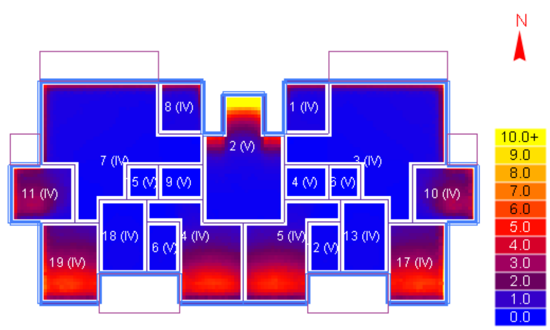
(e) south windowsill height 1.20m



(f) south windowsill height 1.50m



(g) south windowsill height 1.80m



(h) south windowsill height 2.10m

Figure 3.15 Lighting coefficient distribution of south rooms

Source: Author

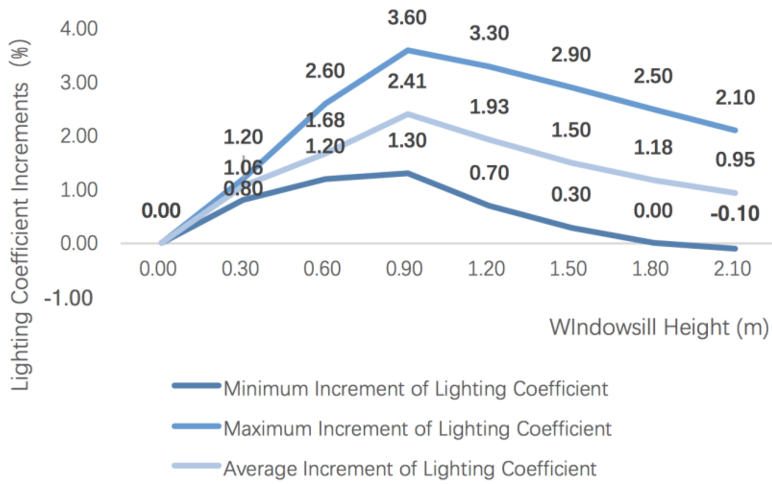


Figure 3.16 Lighting coefficient increments of south rooms caused by south windowsill heights

Source: Author

Combining with the lighting coefficient distribution of south rooms and the data from lighting simulation report, the average lighting coefficient of each room in the south rooms is obtained. Like (1), as shown in Figure 3.16, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a windowsill height of 0.00m. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the south windowsill height, reaches the peak and the inflection point when it is 0.90m; then decreases with the increment of the south windowsill height; according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is different even when the lighting coefficient value are nearly the same, with one windowsill height at 0.60m while another windowsill height at 1.80m; with the windowsill height increasing, the lighting coefficient of the area near windowsill gradually decreases and the lighting coefficient of the area away from windowsill increases. In summary, the average lighting coefficient of the room, quite similar with the (1) part, shows an increasing trend when windowsill height increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the south windowsill height and reaches the turning point of 0.90m, then goes down from the peak.

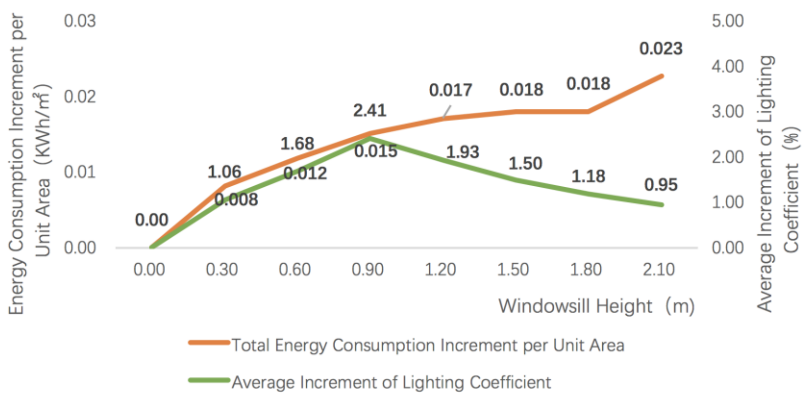


Figure 3.17 Increments of lighting coefficient and total energy consumption caused by south windowsill heights

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.17), which shows the relationships between the south windowsill height, the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. Although the lighting coefficient begins to go down after the peak point when south windowsill height is at 0.90m, the overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way. Comparing to the east counterparts, the values are lower than the east counterparts at a margin. However, the same situation as previously mentioned, the magnitude of energy consumption increment is still so little that can be ignored.

(3) Simulation results of west windowsill height

Table 3.7 The relationship between simulated energy consumption in use phase and west windowsill height (KWh/m^2)

Window/Wall Ratio：East 0.30 South 0.30 West 0.30 North 0.30 Window Height 0.90m Others Parameters as Reference Model								
Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
Annual Cooling Energy Increment	0.000	-0.005	-0.009	-0.012	-0.011	0.000	0.012	0.011
Annual Heating Energy Increment	0.000	0.010	0.020	0.034	0.043	0.047	0.048	0.046
Annual Total Energy Increment	0.000	0.006	0.012	0.021	0.032	0.047	0.060	0.058

Source: Author

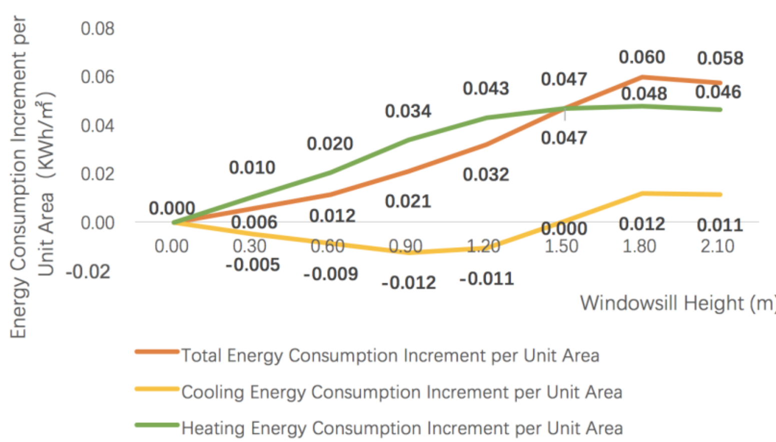
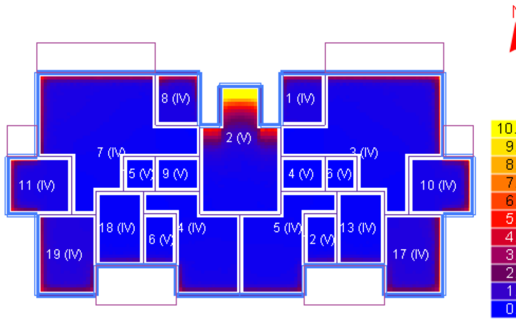


Figure 3.18 Relationship between simulated energy consumption in use phase and west windowsill height

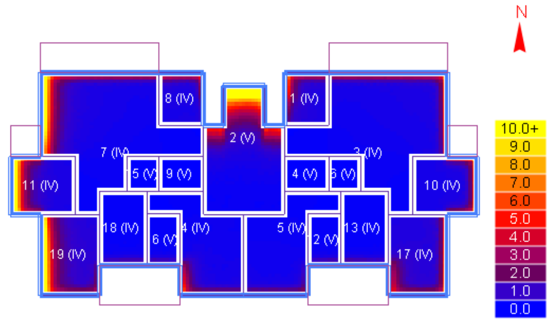
Source: Author

Table 3.7 and Figure 3.18 show the energy consumption changes in use phase caused by west windowsill height. The values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a windowsill height of 0.00m. Same as the east counterpart, it can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the energy consumption of heating increases with the increment of the west windowsill height while the other parameters staying the same; the cooling energy consumption decreases with the increase of the west windowsill height, reaches its peak when west windowsill height is at 0.90m and then goes up; however, similarly with mentioned previously, the change of total energy consumption per unit area still shows a positive correlation with the increase of the west windowsill height, the maximum incremental value is 0.060KWh/m^2 when the windowsill height is 1.80m. Although the value is still little, comparing to the counterparts of east and south, it is a significant increment. However, given the magnitude of the incremental value is little, it still can be considered that the east windowsill height has little influence on the energy consumption in use phase of residential building.

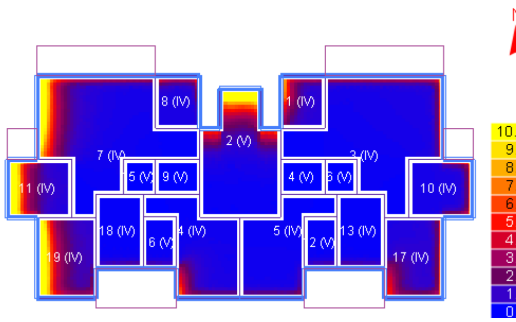
The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.19).



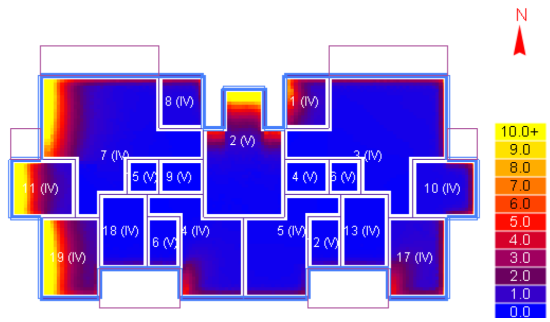
(a) west windowsill height 0.00m



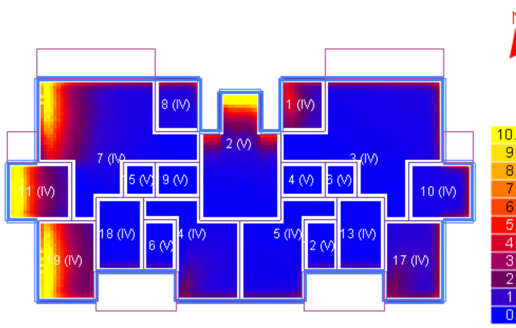
(b) west windowsill height 0.30m



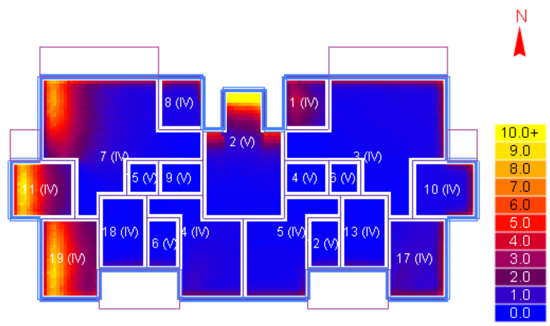
(c) west windowsill height 0.60m



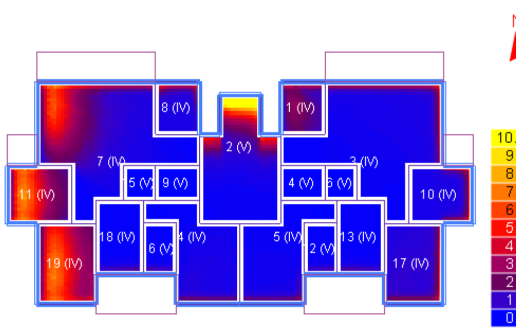
(d) west windowsill height 0.90m



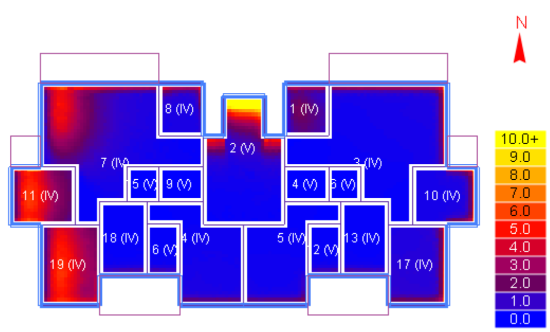
(e) west windowsill height 1.20m



(f) west windowsill height 1.50m



(g) west windowsill height 1.80m



(h) west windowsill height 2.10m

Figure 3.19 Lighting coefficient distribution of west rooms

Source: Author

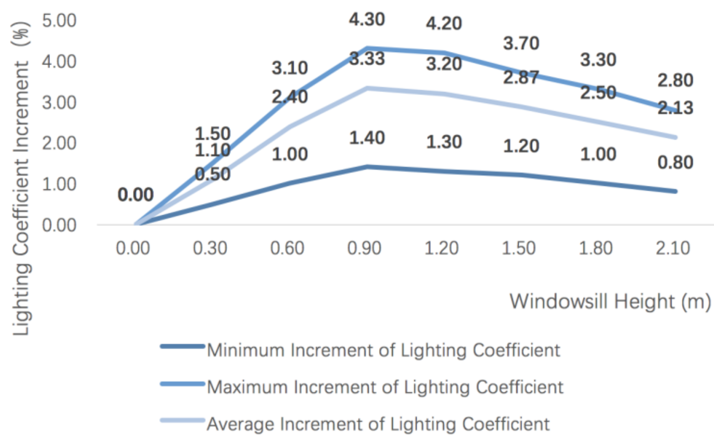


Figure 3.20 Lighting coefficient increments of west rooms

caused by west windowsill heights

Source: Author

Combining with the lighting coefficient distribution of west rooms and the data from lighting simulation report, the average lighting coefficient of each room in the west rooms is obtained (Figure 3.19). Like mentioned previously, as shown in Figure 3.20, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a windowsill height of 0.00m. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the west windowsill height, reaches the peak and the inflection point when it is 0.90m; then decreases with the increment of the west windowsill height; according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is different even when the lighting coefficient value are nearly the same, with one windowsill height at 0.60m while another windowsill height at 1.80m; with the windowsill height increasing, the lighting coefficient of the area near windowsill gradually decreases and the lighting coefficient of the area away from windowsill increases. In conclusion, the average lighting coefficient of the room, quite similar with the east counterpart, shows an increasing trend when windowsill height increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the west windowsill height and reaches the turning point of 0.90m, then goes down from the peak.

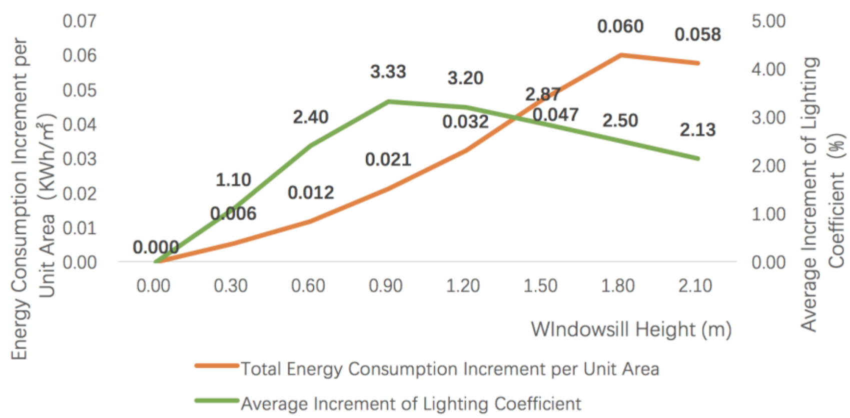


Figure 3.21 Increments of lighting coefficient and total energy consumption caused by west windowsill heights

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.21), which shows the relationships between the west windowsill height, the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. Although the lighting coefficient begins to go down after the peak point when west windowsill height is at

0.90m, the overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way. However, the same situation as previously mentioned, the magnitude of energy consumption increment is still so little that can be ignored in our decision-making phase.

(4) Simulation results of north windowsill height

Table 3.8 The relationship between simulated energy consumption in use phase and north windowsill height (KWh/m^2)

Window/Wall Ratio：East 0.30 South 0.30 West 0.30 North 0.30 Window Height 0.90m Others Parameters as Reference Model								
Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
Annual Cooling Energy Increment	0.000	-0.036	-0.071	-0.105	-0.112	-0.107	-0.102	-0.096
Annual Heating Energy Increment	0.000	0.048	0.096	0.141	0.152	0.151	0.149	0.148
Annual Total Energy Increment	0.000	0.012	0.025	0.036	0.040	0.044	0.047	0.052

Source: Author

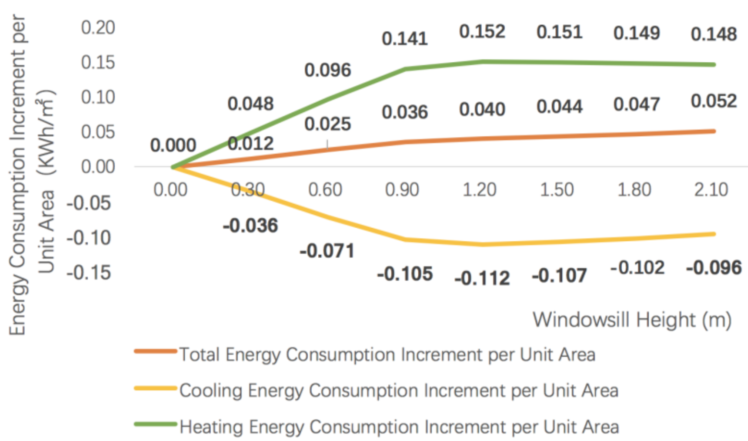
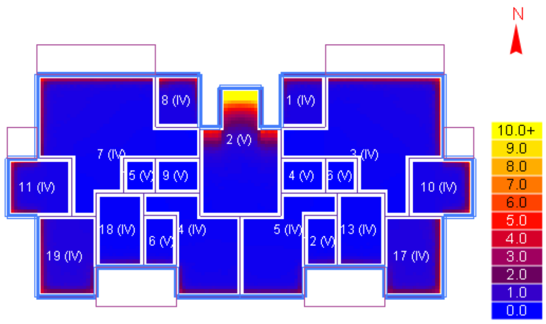


Figure 3.22 Relationship between simulated energy consumption in use phase and north windowsill height

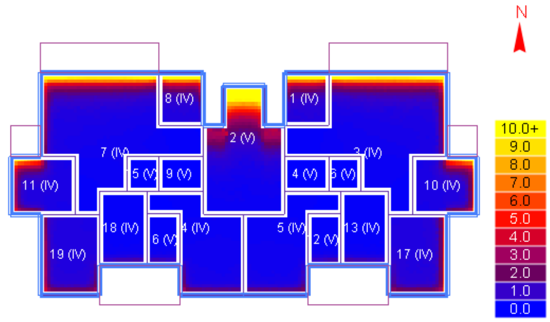
Source: Author

Table 3.8 and Figure 3.22 show the energy consumption changes in use phase caused by north windowsill height. The values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a windowsill height of 0.00m. Same as the south counterpart, it can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the energy consumption of heating increases with the increment of the north windowsill height while the other parameters staying the same; the cooling energy consumption decreases with the increase of the north windowsill height, reaches its peak when north windowsill height is at 1.20m and then goes up; however, similarly with mentioned previously, the change of total energy consumption per unit area still shows a positive correlation with the increase of the north windowsill height, the maximum incremental value is 0.052KWh/m^2 when the windowsill height is 2.10m. Although the value is still little, comparing to the counterparts of east and south, it is a significant increment, quite similar as the west. However, given the magnitude of the incremental value is little, it still can be considered that the east windowsill height has little influence on the energy consumption in use phase of residential building.

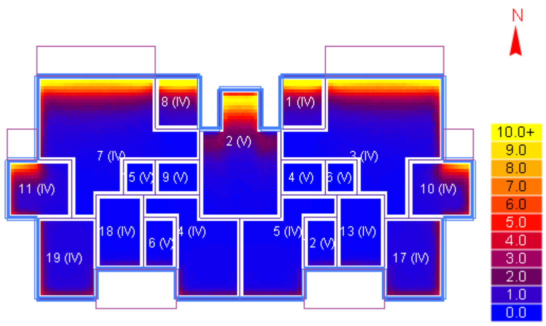
Then the lighting simulation was conducted for the corresponding models respectively. And the figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.23).



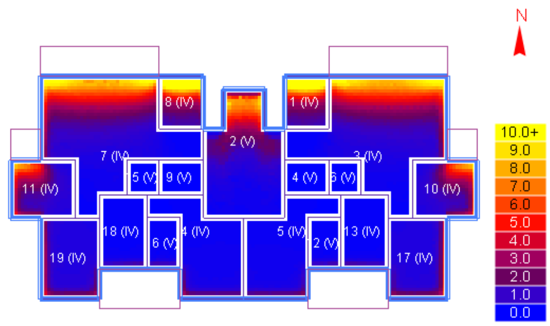
(a) north windowsill height 0.00m



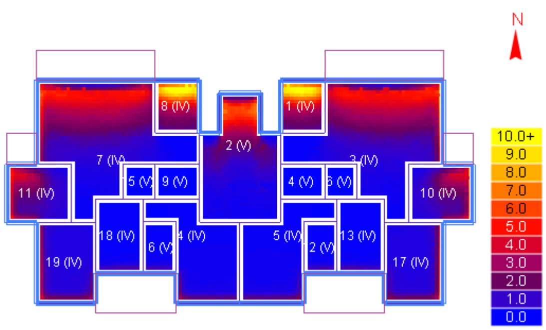
(b) north windowsill height 0.30m



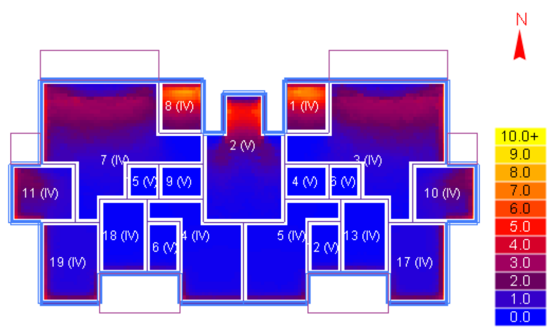
(c) north windowsill height 0.60m



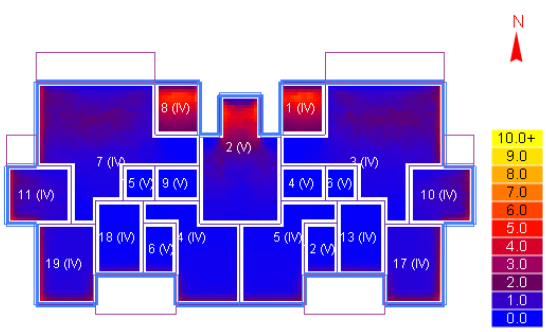
(d) north windowsill height 0.90m



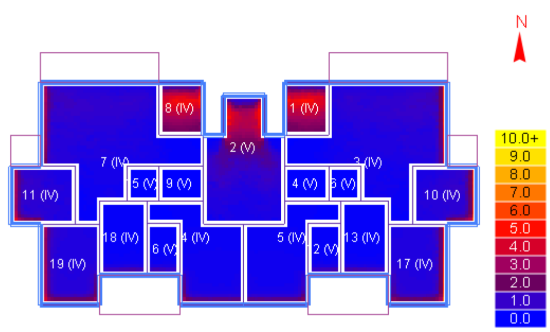
(e) north windowsill height 1.20m



(f) north windowsill height 1.50m



(g) north windowsill height 1.80m



(h) north windowsill height 2.10m

Figure 3.23 Lighting coefficient distribution of north rooms

Source: Author

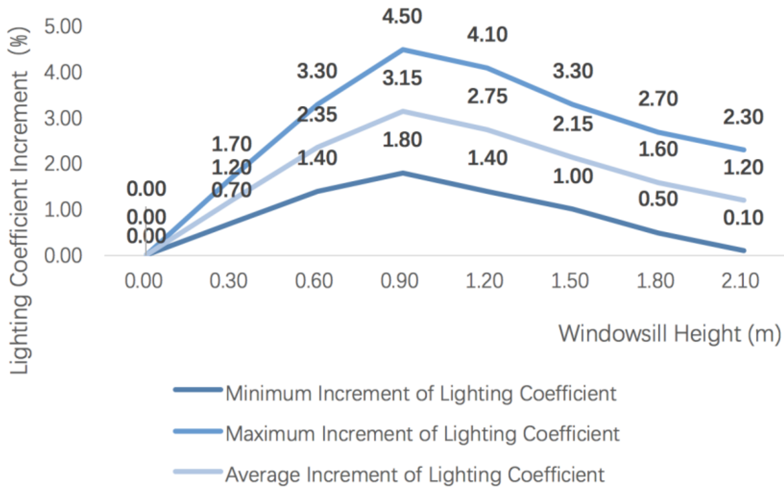


Figure 3.24 Lighting coefficient increments of north rooms

caused by north windowsill heights

Source: Author

Combining with the lighting coefficient distribution of north rooms and the data from lighting simulation report, the average lighting coefficient of each room in the north rooms is obtained (Figure 3.23). Like mentioned previously, as shown in Figure 3.24, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a windowsill height of 0.00m. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the north windowsill height, reaches the peak and the inflection point when it is 0.90m; then decreases with the increment of the north windowsill height; with the windowsill height increasing, the lighting coefficient of the area near windowsill gradually decreases and the lighting coefficient of the area away from windowsill increases. In conclusion, the average lighting coefficient of the room, quite similar with the other counterparts, shows an increasing trend when windowsill height increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the north windowsill height and reaches the turning point of 0.90m, then goes down from the peak.

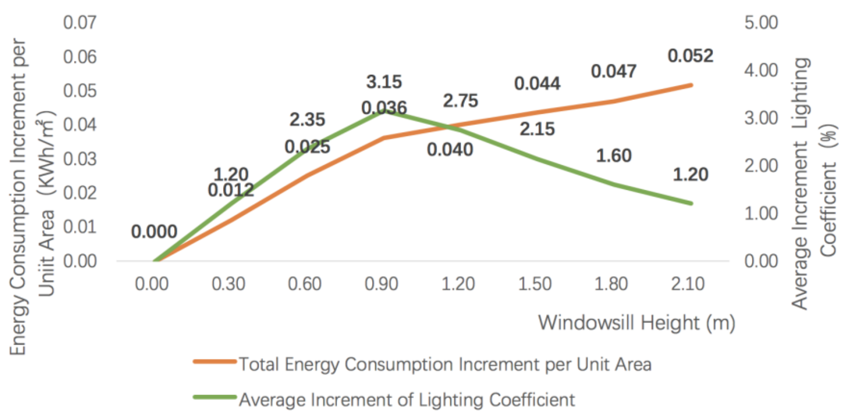


Figure 3.25 Increments of lighting coefficient and total energy consumption caused by north windowsill heights

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.25), which shows the relationships between the north windowsill height, the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. Although the lighting coefficient begins to go down after the peak point when north windowsill height is at 0.90m, the overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way. However, the same situation as previously mentioned, the magnitude of energy consumption increment is still so little that can be ignored in our decision-making phase.

(5) Simulation results of east window/wall ratio

Table 3.9 The Relationship between simulated energy consumption in use phase and east window/wall ratio (window width) (KWh/m^2)

Windowsill Height 0.00m	Window height as Floor Height					Others Parameters as Reference Model					
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	1.12	2.25	3.68	4.64	5.87	7.07	7.99	8.97	10.07	10.58
Annual Heating Energy Increment	0.00	0.43	0.94	1.78	2.32	3.08	3.62	4.23	4.65	5.21	5.45
Annual Total Energy Increment	0.00	1.55	3.19	5.46	6.96	8.95	10.69	12.22	13.62	15.28	16.04

Source: Author

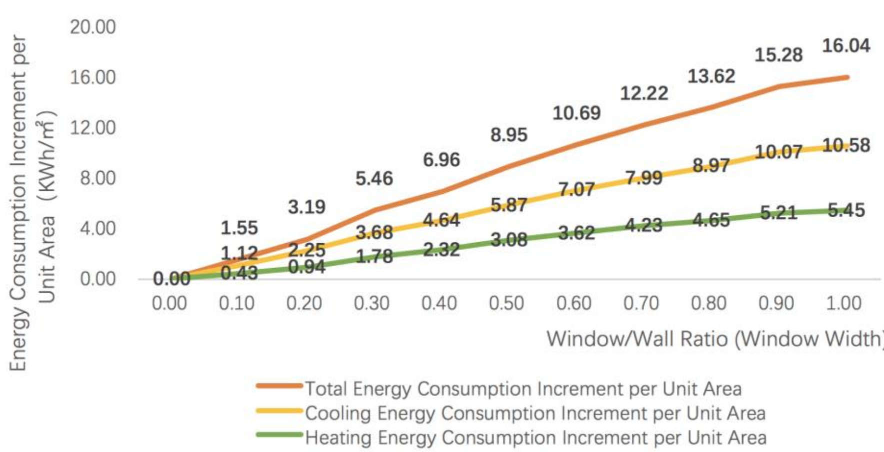
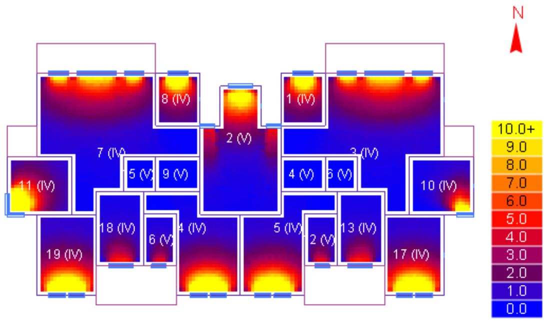


Figure 3.26 Relationship between simulated energy consumption in use phase and east window/wall ratio (window width)

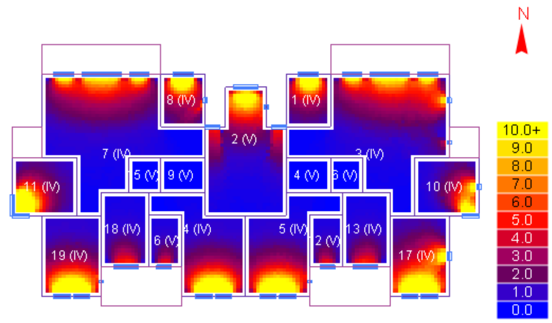
Source: Author

Table 3.9 and Figure 3.26 show the energy consumption changes in use phase caused by east window/wall ratio (window width). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the east window/wall ratio (window width) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the east window/wall ratio (window width), the maximum incremental value is 16.04KWh/m^2 when the window/wall ratio is 1.00. Given the magnitude of the incremental value is much bigger than the counterparts of the windowsill, it can be considered that the east window/wall ratio has significant influence on the energy consumption in use phase of residential building.

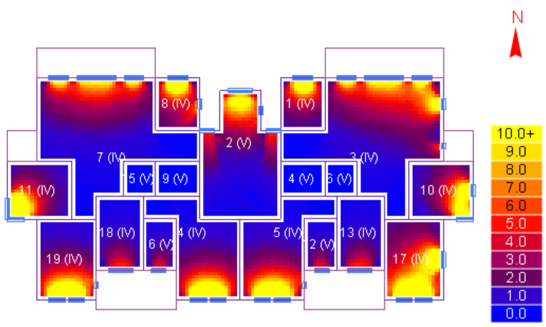
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different east window/wall ratio (window width) were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.27).



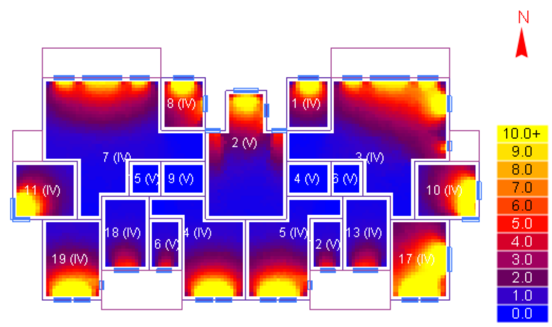
(a) east window/wall ratio 0.00



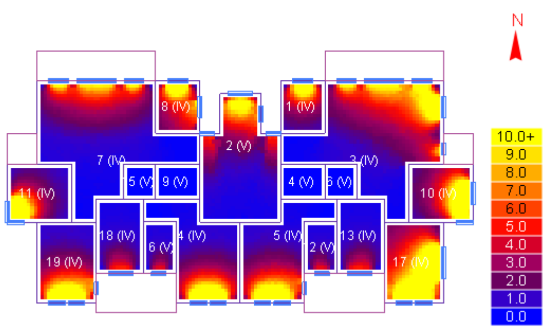
(b) east window/wall ratio 0.10



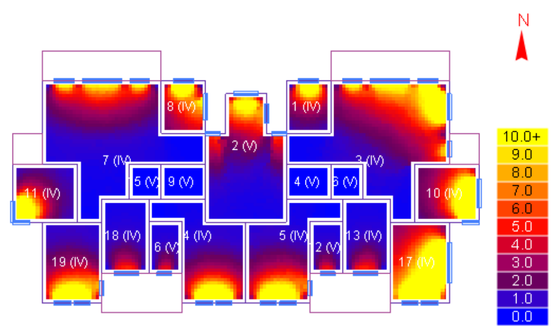
(c) east window/wall ratio 0.20



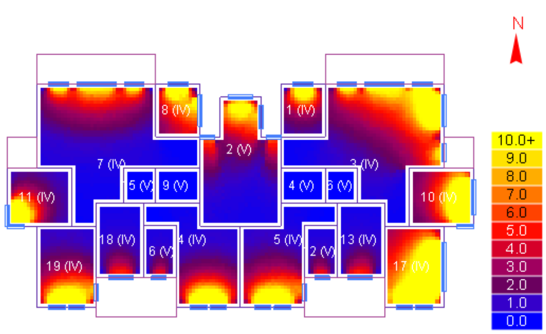
(d) east window/wall ratio 0.30



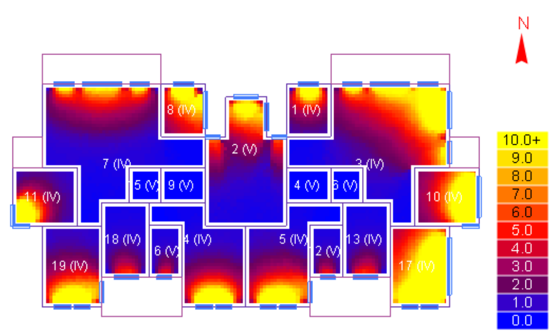
(e) east window/wall ratio 0.40



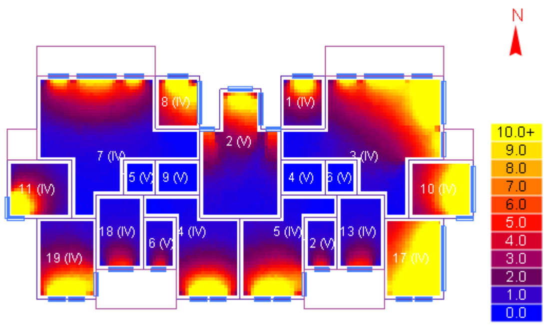
(f) east window/wall ratio 0.50



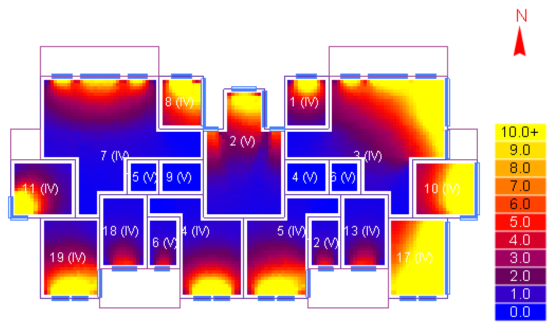
(g) east window/wall ratio 0.60



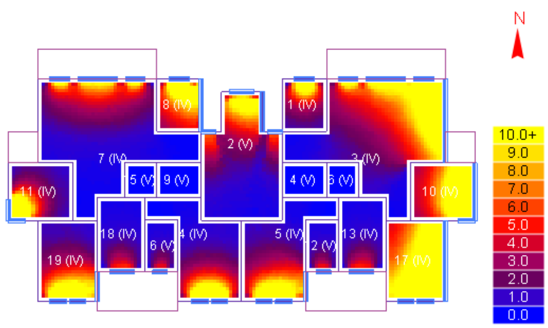
(h) east window/wall ratio 0.70



(i) east window/wall ratio 0.80



(j) east window/wall ratio 0.90



(k) east window/wall ratio 1.00

Figure 3.27 Lighting coefficient distribution of east rooms (with change of window width)

Source: Author

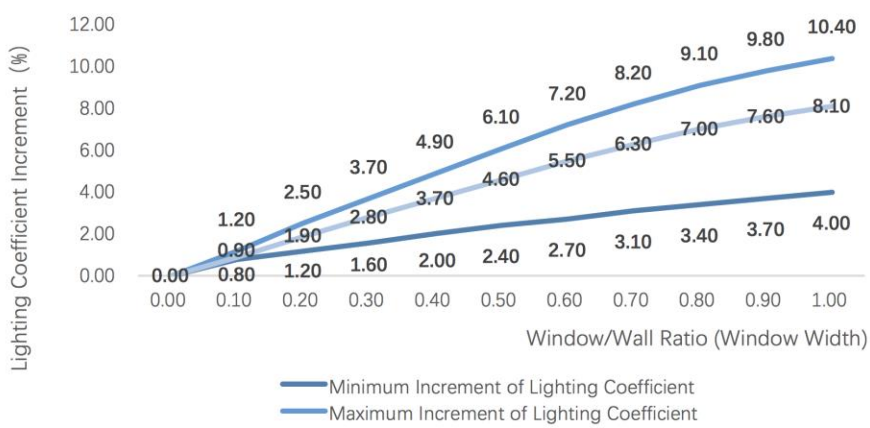


Figure 3.28 Lighting coefficient increments of east rooms caused by east window/wall ratio (window width)

Source: Author

Combining with the lighting coefficient distribution of east rooms and the data from lighting simulation report, the average lighting coefficient of each room in the east rooms is obtained. As shown in Figure 3.28, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window width) at 0.00. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the east window/wall ratio (window width); according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window width) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the east window/wall ratio (window width).

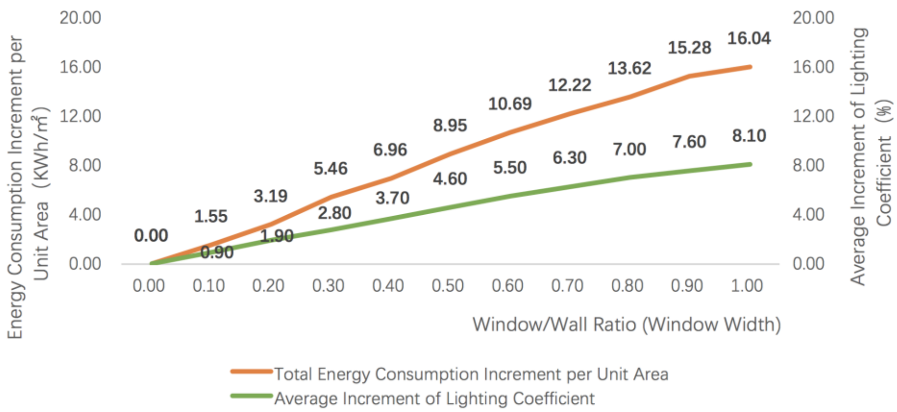


Figure 3.29 Increments of lighting coefficient and total energy consumption caused by east window/wall ratio (window width)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient is reflected in the same chart (Figure 3.29), which shows the relationships between the east window/wall ratio (window width), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way. However, in the meantime, the magnitude of energy consumption increment is so significant that can be ignored in our decision-making phase.

Table 3.10 The relationship between simulated energy consumption in use phase and east window/wall ratio (window height) (KWh/m^2)

Windowsill Height 0.00m	Window Width as East Exterior Wall Width						Others Parameters as Reference Model				
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	1.08	2.25	3.42	4.56	5.73	6.82	7.88	8.94	10.00	10.58
Annual Heating Energy Increment	0.00	0.48	1.02	1.82	2.43	3.06	3.63	4.17	4.70	5.22	5.45
Annual Total Energy Increment	0.00	1.56	3.27	5.23	6.99	8.79	10.45	12.04	13.63	15.22	16.04

Source: Author

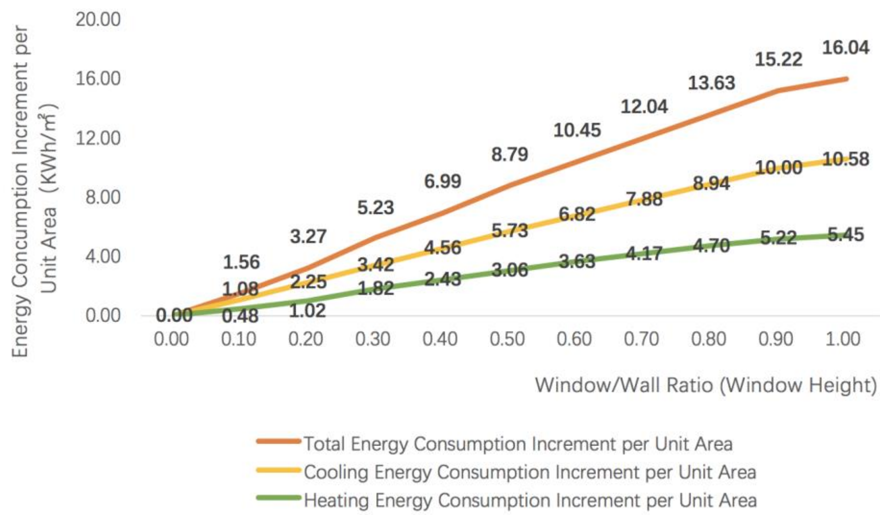
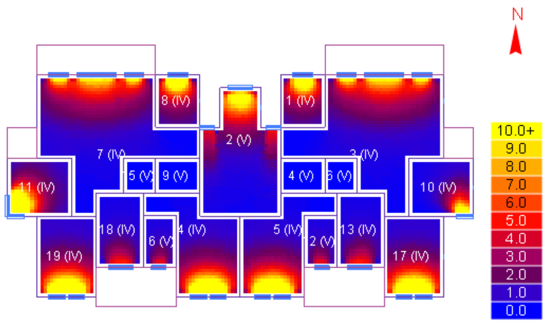


Figure 3.30 Relationship between simulated energy consumption in use phase and east window/wall ratio (window height)

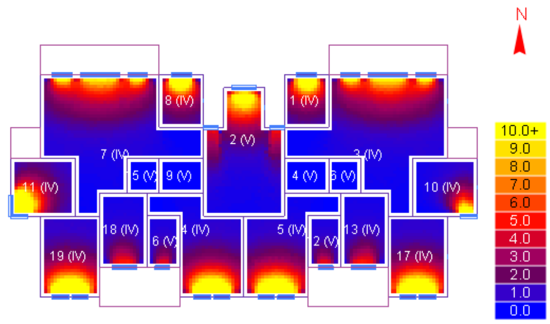
Source: Author

Table 3.10 and Figure 3.30 show the energy consumption changes in use phase caused by east window/wall ratio (window height). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the east window/wall ratio (window height) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the east window/wall ratio, the maximum incremental value is 16.04KWh/m^2 when the window/wall ratio is 1.00. Given the data collected above, it can be seen that the window shape does not have significant influence on the energy consumption in use phase of residential building, while the window/wall ratio do have.

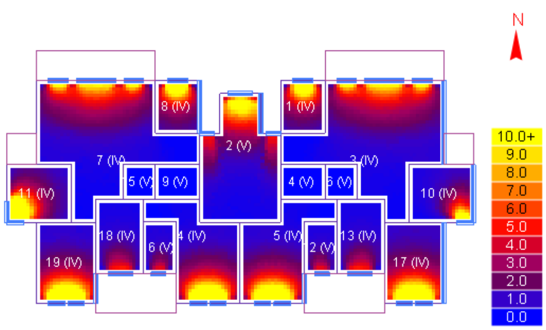
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different east window/wall ratio (window height) were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.31).



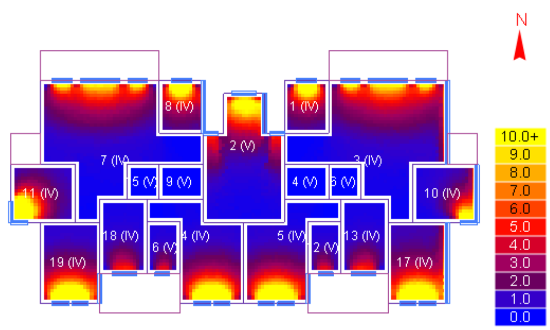
(a) east window/wall ratio 0.00



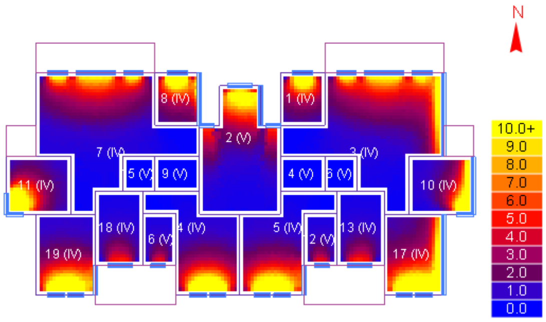
(b) east window/wall ratio 0.10



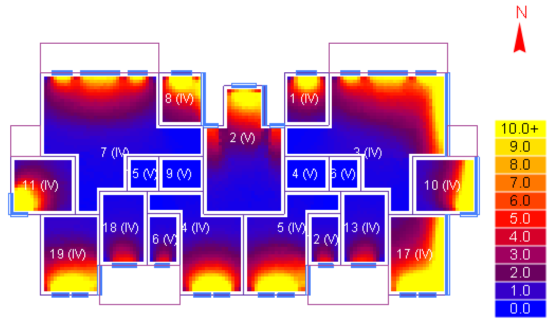
(c) east window/wall ratio 0.20



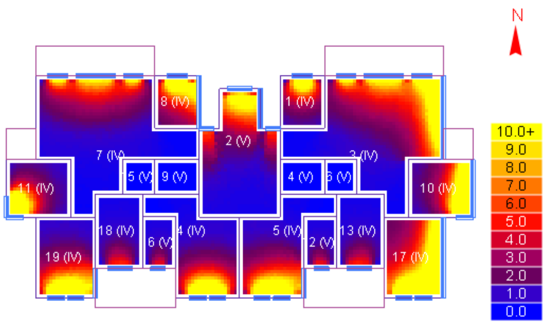
(d) east window/wall ratio 0.30



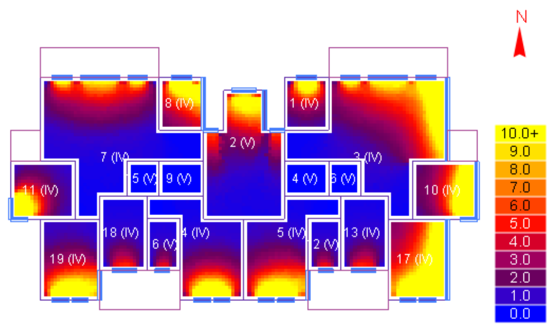
(e) east window/wall ratio 0.40



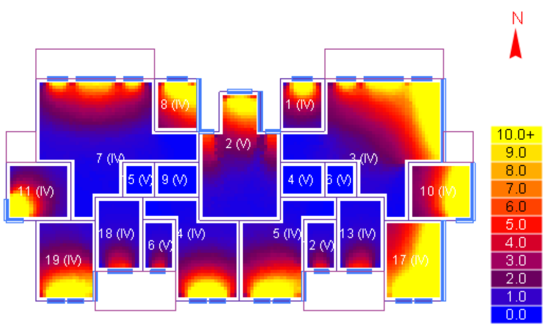
(f) east window/wall ratio 0.50



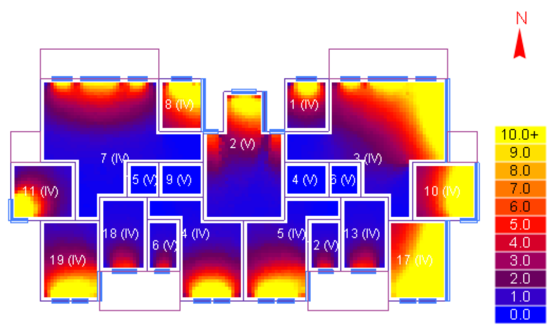
(g) east window/wall ratio 0.60



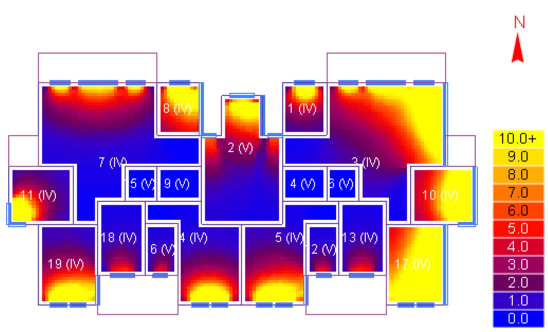
(h) east window/wall ratio 0.70



(i) east window/wall ratio 0.80



(j) east window/wall ratio 0.90



(k) east window/wall ratio 1.00

Figure 3.31 Lighting coefficient distribution of east rooms (with change of window height)

Source: Author

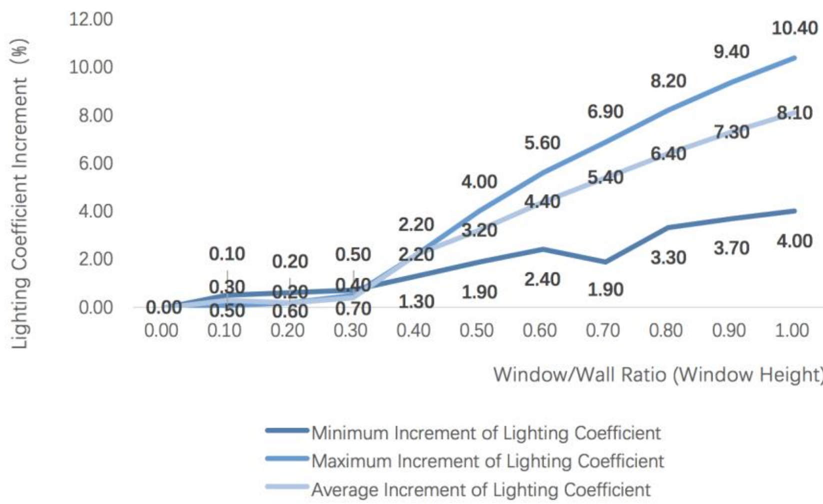


Figure 3.32 Lighting coefficient increments of east rooms caused by east window/wall ratio (window height)

Source: Author

Combining with the lighting coefficient distribution of east rooms and the data from lighting simulation report, the average lighting coefficient of each room in the east rooms is obtained. As shown in Figure 3.28, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window height) at 0.00. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the east window/wall ratio (window height) when the ratio is beyond 0.30; according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window height) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the east window/wall ratio (window height).

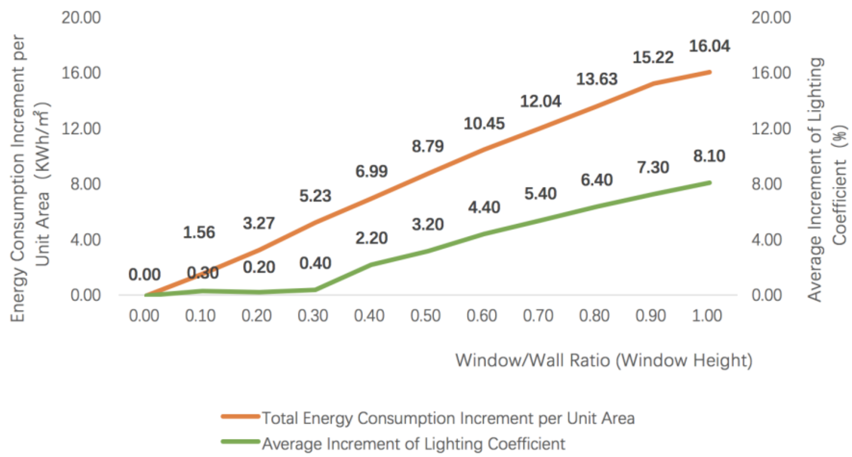


Figure 3.33 Increments of lighting coefficient and total energy consumption caused by east window/wall ratio (window height)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.33), which shows the relationships between the east window/wall ratio (window height), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way when the ratio is beyond 0.30. However, in the meantime, the magnitude of energy consumption increment is so significant that cannot be ignored in our decision-making phase.

(6) Simulation results of south window/wall ratio

Table 3.11 The relationship between simulated energy consumption in use phase and south window/wall ratio (window width) (KWh/m^2)

Windowsill Height 0.00m	Window height as Floor Height				Others Parameters as Reference Model						
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	0.96	1.99	3.02	4.20	5.61	7.10	8.65	10.15	11.80	12.67
Annual Heating Energy Increment	0.00	0.17	0.57	0.93	1.61	2.66	3.96	5.32	6.86	8.34	9.02
Annual Total Energy Increment	0.00	1.13	2.57	3.95	5.80	8.27	11.07	13.97	17.00	20.13	21.68

Source: Author

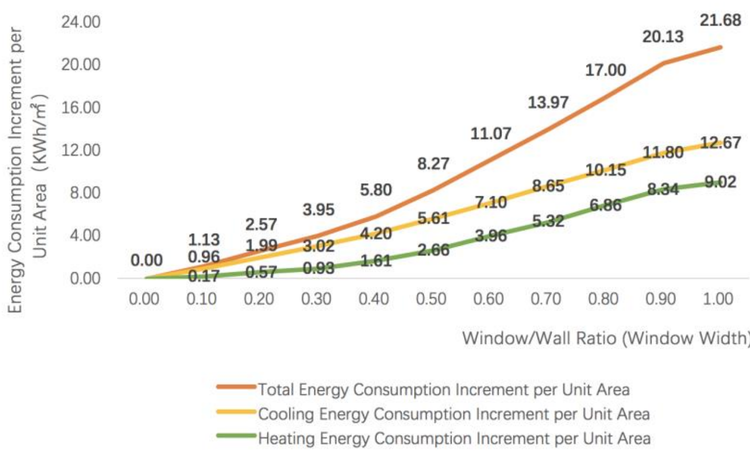
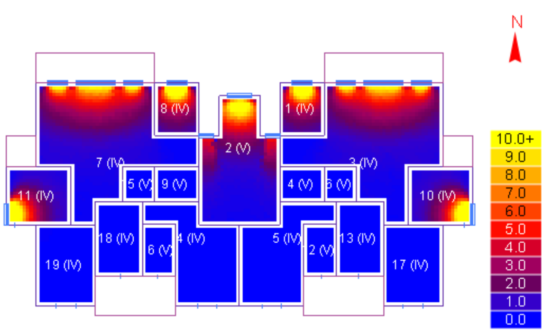


Figure 3.34 Relationship between simulated energy consumption in use phase and south window/wall ratio (window width)

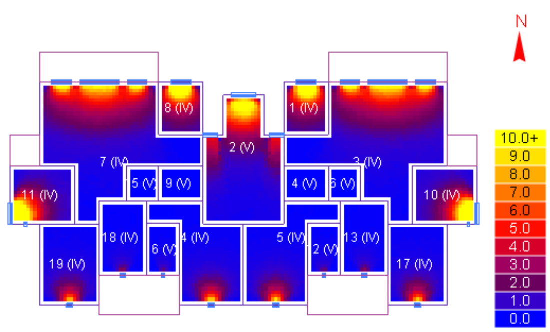
Source: Author

Table 3.11 and Figure 3.34 show the energy consumption changes in use phase caused by south window/wall ratio (window width). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the south window/wall ratio (window width) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the south window/wall ratio (window width), the maximum incremental value is 21.68KWh/m^2 when the window/wall ratio is 1.00, a significant increment than the 16.04KWh/m^2 of the east counterpart. It can be considered that the south window/wall ratio has more influence on the energy consumption in use phase of residential building than the east counterpart.

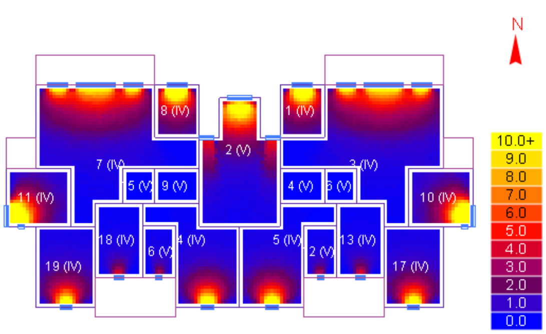
The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.35).



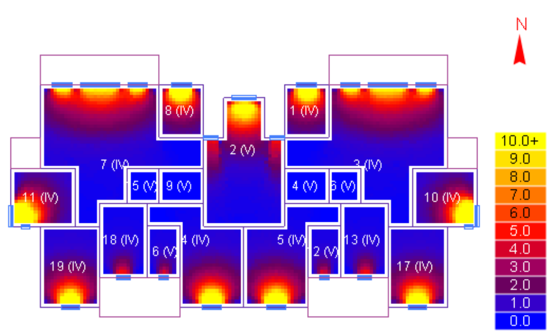
(a) south window/wall ratio 0.00



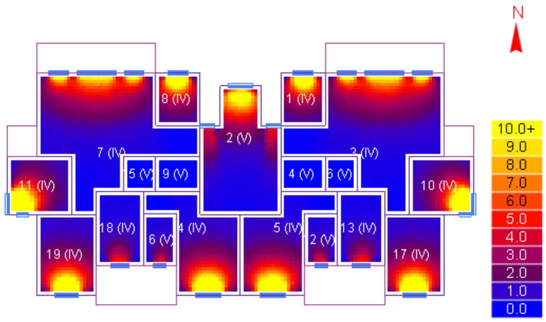
(b) south window/wall ratio 0.10



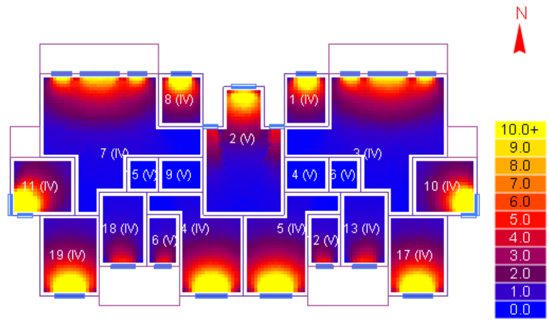
(c) south window/wall ratio 0.20



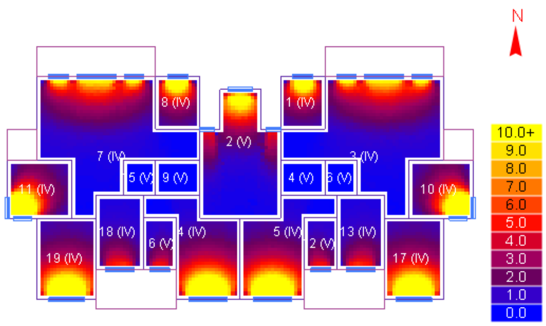
(d) south window/wall ratio 0.30



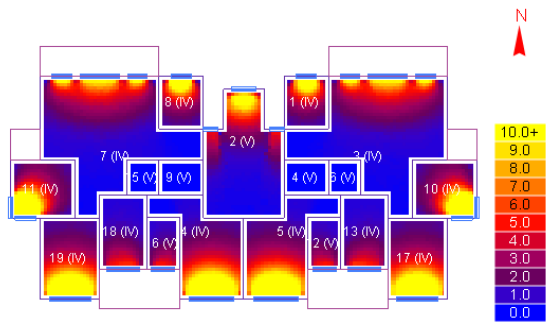
(e) south window/wall ratio 0.40



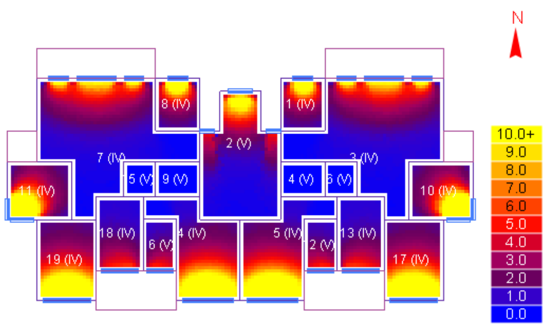
(f) south window/wall ratio 0.50



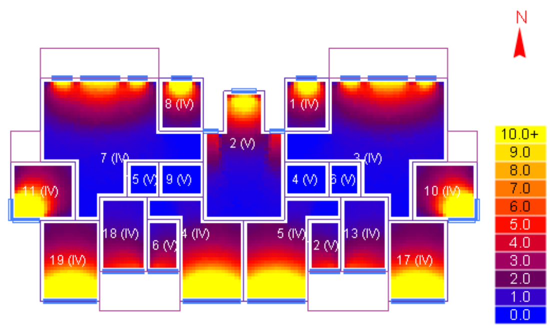
(g) south window/wall ratio 0.60



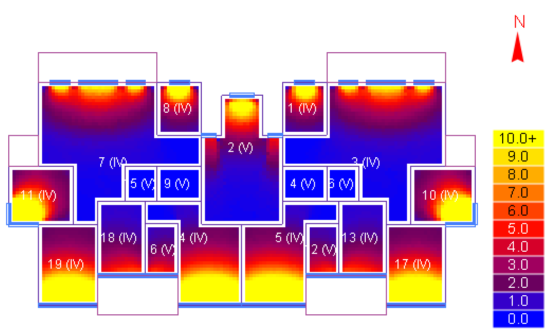
(h) south window/wall ratio 0.70



(i) south window/wall ratio 0.80



(j) south window/wall ratio 0.90



(k) south window/wall ratio 1.00

Figure 3.35 Lighting coefficient distribution of south rooms (with change of window width)

Source: Author

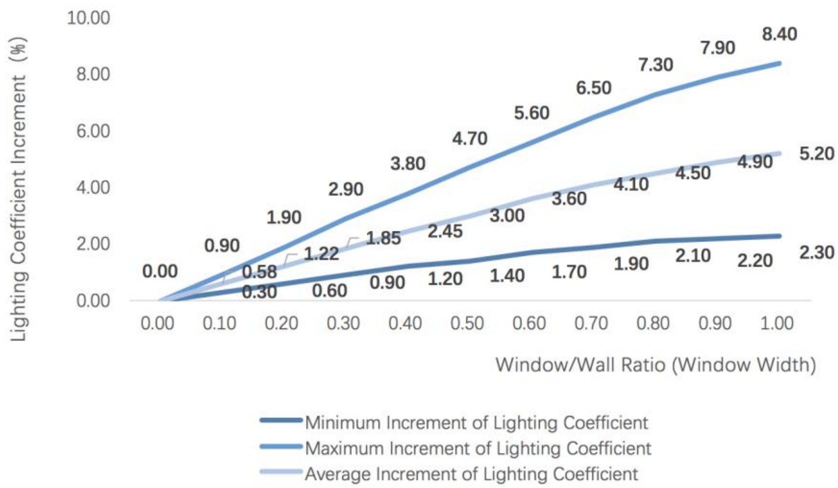


Figure 3.36 Lighting coefficient increments of south rooms caused by south window/wall ratio (window width)

Source: Author

Combining with the lighting coefficient distribution of south rooms and the data from lighting simulation report, the average lighting coefficient of each room in the south rooms is obtained. As shown in Figure 3.36, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window width) at 0.00. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the south window/wall ratio (window width); according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window width) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the south window/wall ratio (window width).

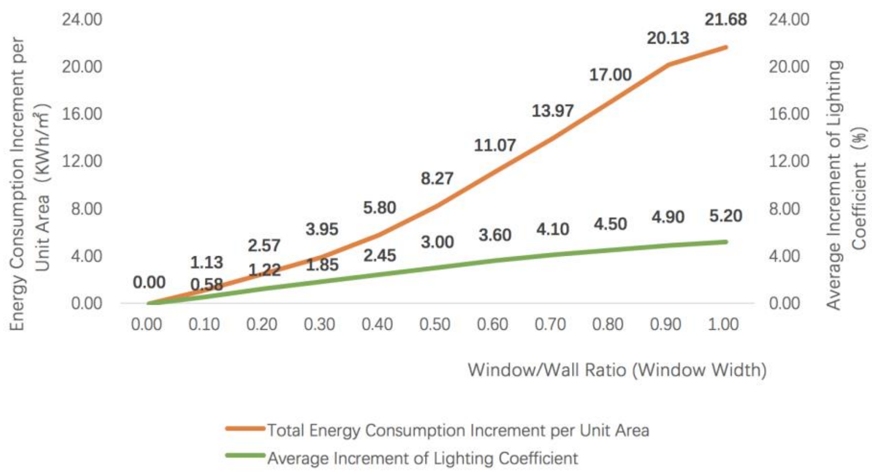


Figure 3.37 Increments of lighting coefficient and total energy consumption caused by south window/wall ratio (window width)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient is reflected in the same chart (Figure 3.37), which shows the relationships between the south window/wall ratio (window width), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The difference of growth rate of the two curves representing energy consumption and lighting coefficient is obvious and higher than the east counterpart. Thus, it means more energy will be used to get the same lighting effect by raising the window/wall ratio in south windows.

Table 3.12 The relationship between simulated energy consumption in use phase and south window/wall ratio (window height) (KWh/m^2)

Windowsill Height 0.00m	Window Width as South Exterior Wall Width						Others Parameters as Reference Model				
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	0.96	1.99	3.01	4.14	6.01	6.94	8.94	9.82	11.40	12.67
Annual Heating Energy Increment	0.00	0.13	0.49	0.85	1.48	2.83	3.92	5.44	6.83	8.29	9.02
Annual Total Energy Increment	0.00	1.09	2.47	3.87	5.62	8.85	10.85	14.37	16.65	19.69	21.68

Source: Author

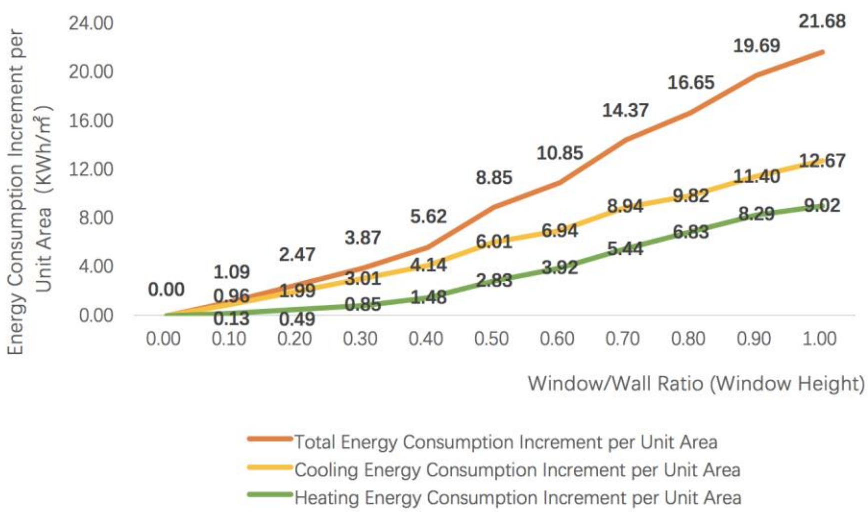
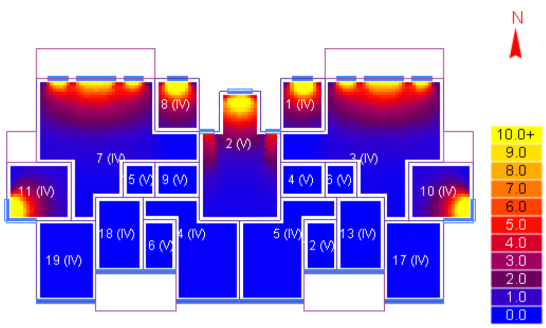


Figure 3.38 Relationship between simulated energy consumption in use phase and south window/wall ratio (window height)

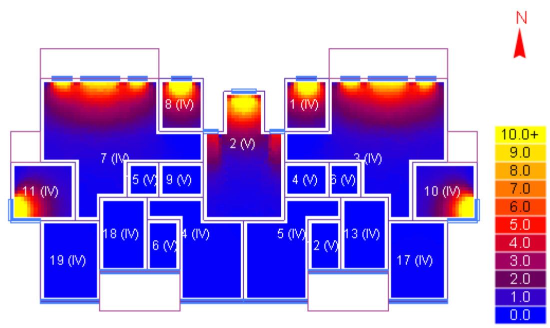
Source: Author

Table 3.12 and Figure 3.38 show the energy consumption changes in use phase caused by south window/wall ratio (window height). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the south window/wall ratio (window height) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the south window/wall ratio.

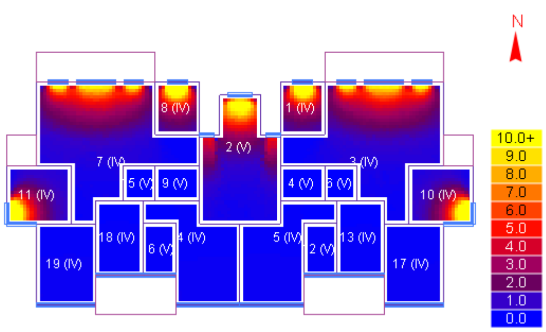
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different south window/wall ratio (window height) were obtained. The figure of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.39).



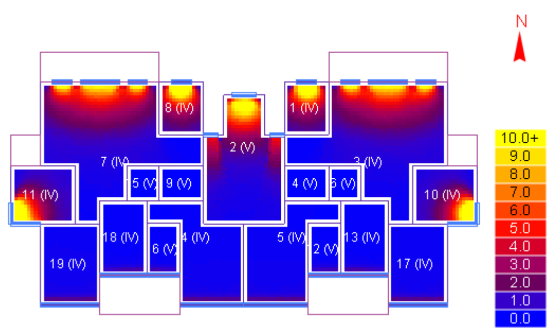
(a) south window/wall ratio 0.00



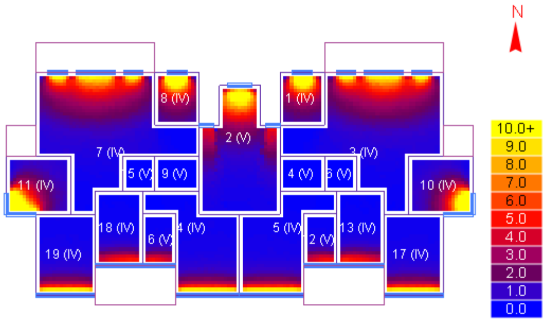
(b) south window/wall ratio 0.10



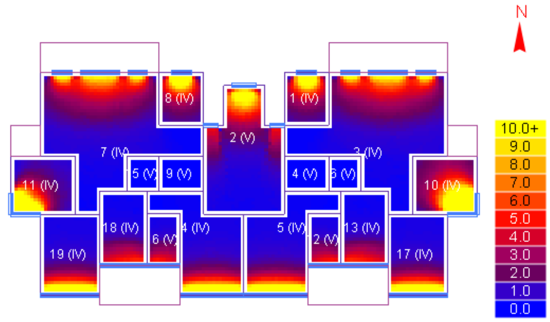
(c) south window/wall ratio 0.20



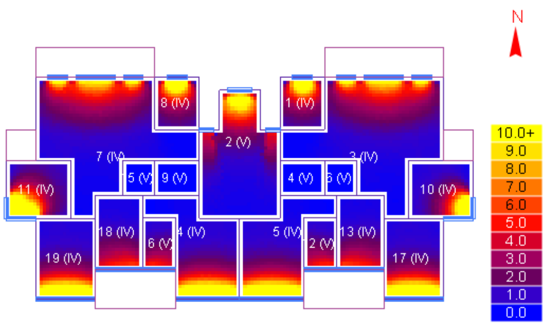
(d) south window/wall ratio 0.30



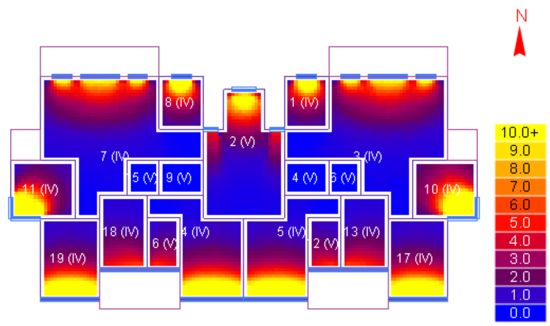
(e) south window/wall ratio 0.40



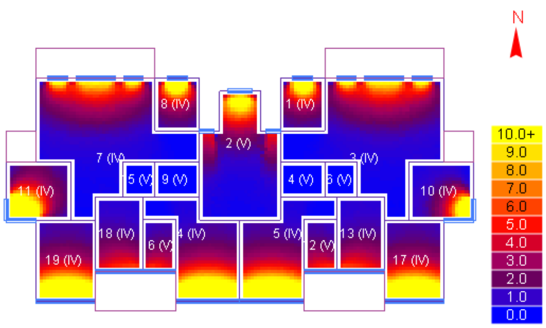
(f) south window/wall ratio 0.50



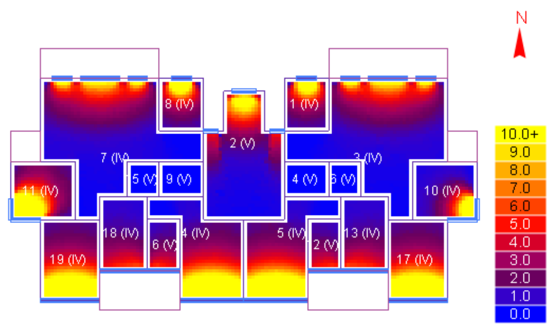
(g) south window/wall ratio 0.60



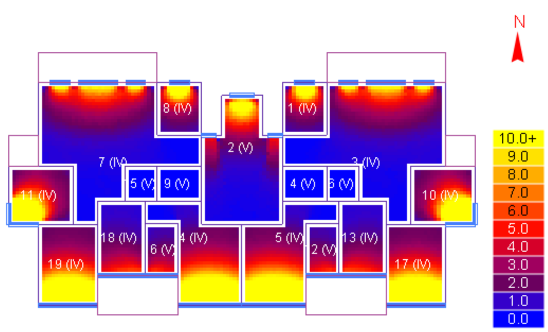
(h) south window/wall ratio 0.70



(i) south window/wall ratio 0.80



(j) south window/wall ratio 0.90



(k) south window/wall ratio 1.00

Figure 3.39 Lighting coefficient distribution of south rooms (with the change of window height)

Source: Author

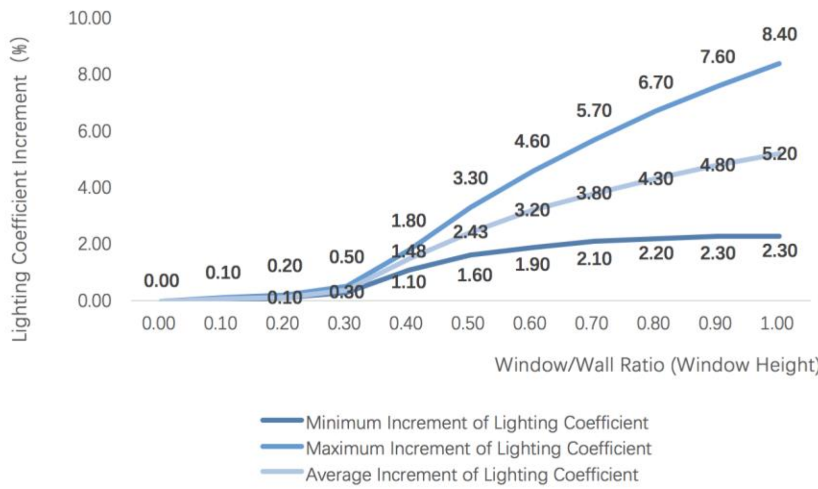


Figure 3.40 Lighting coefficient increments of south rooms caused by south window/wall ratio (window height)

Source: Author

Combining with the lighting coefficient distribution of south rooms and the data from lighting simulation report, the average lighting coefficient of each room in the south rooms is obtained. As shown in Figure 3.40, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window height) at 0.00. Similar with the east counterpart, the lighting coefficient increases with the increment of the south window/wall ratio (window height) when the ratio is beyond 0.30; the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window height) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the south window/wall ratio (window height).

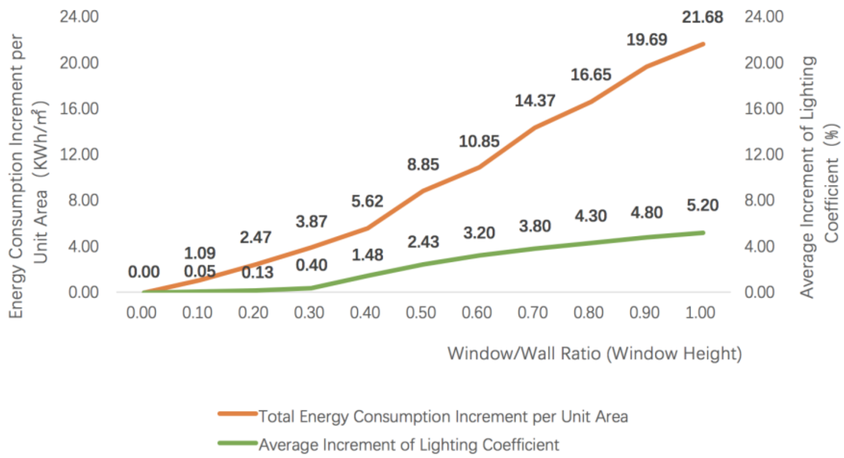


Figure 3.41 Increments of lighting coefficient and total energy consumption caused by south window/wall ratio (window height)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.41), which shows the relationships between the south window/wall ratio (window height), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way when the ratio is beyond 0.30 while the trend is not obvious when it is below 0.30.

(7) Simulation results of west window/wall ratio

Table 3.13 The relationship between simulated energy consumption in use phase and west window/wall ratio (window width) (KWh/m^2)

Windowsill Height 0.00m	Window height as Floor Height				Others Parameters as Reference Model						
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	1.00	2.01	2.98	3.98	4.92	5.98	6.91	7.85	8.67	9.18
Annual Heating Energy Increment	0.00	0.68	1.39	2.05	2.71	3.62	4.09	4.68	5.28	5.87	6.02
Annual Total Energy Increment	0.00	1.67	3.40	5.03	6.69	8.55	10.07	11.59	13.13	14.54	15.19

Source: Author

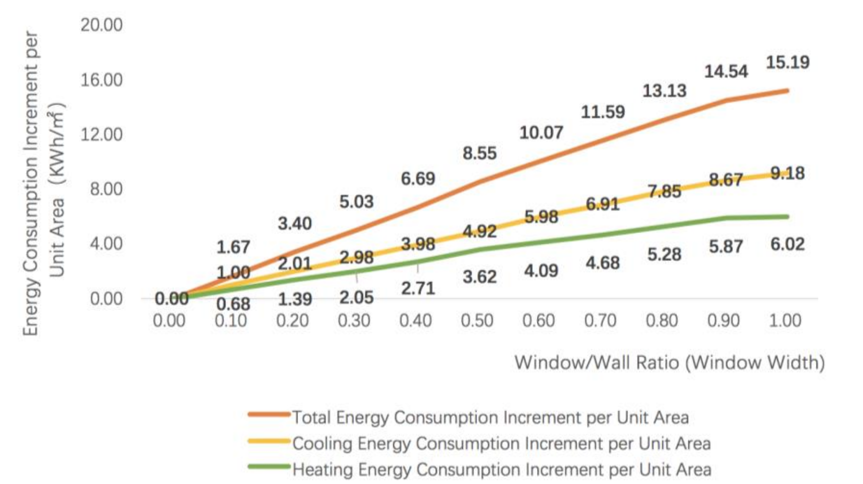
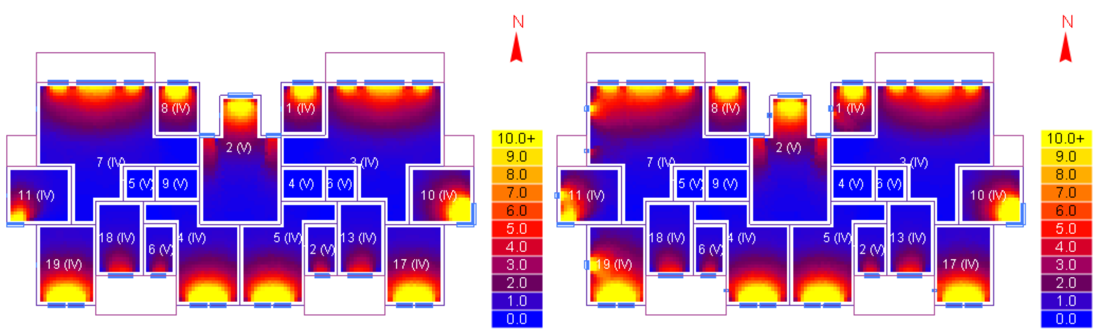


Figure 3.42 Relationship between simulated energy consumption in use phase and west window/wall ratio (window width)

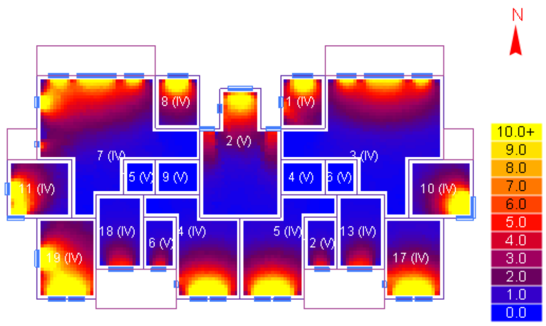
Source: Author

Table 3.13 and Figure 3.42 show the energy consumption changes in use phase caused by west window/wall ratio (window width). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the west window/wall ratio (window width) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the west window/wall ratio (window width), the maximum incremental value is 15.19KWh/m^2 when the window/wall ratio is 1.00, close to the 16.04KWh/m^2 of the east counterpart, significant less than the south counterpart. It can be considered that the west window/wall ratio has close influence on the energy consumption in use phase of residential building as the east counterpart, less impact than the south counterpart.

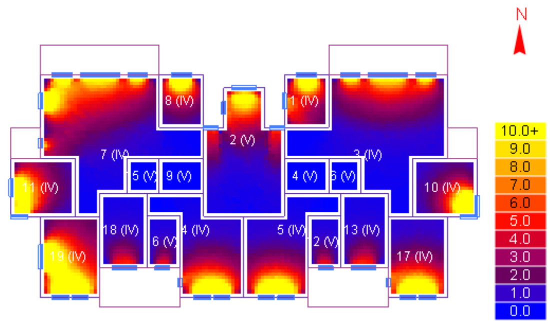
Then the lighting simulation was conducted for the corresponding models respectively. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.43).



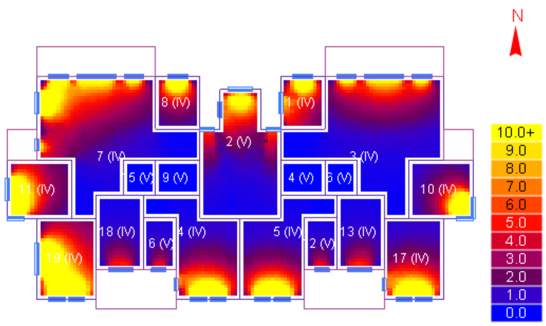
(a) west window/wall ratio 0.00 (b) west window/wall ratio 0.10



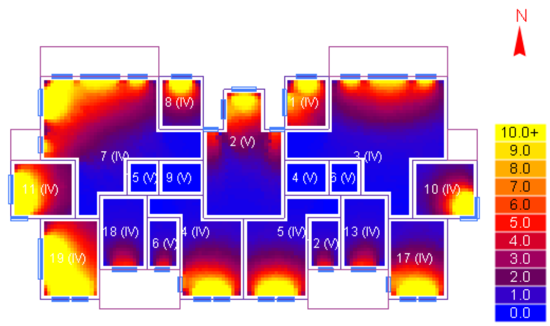
(c) west window/wall ratio 0.20



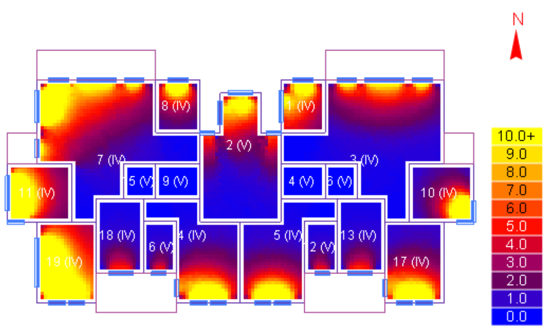
(d) west window/wall ratio 0.30



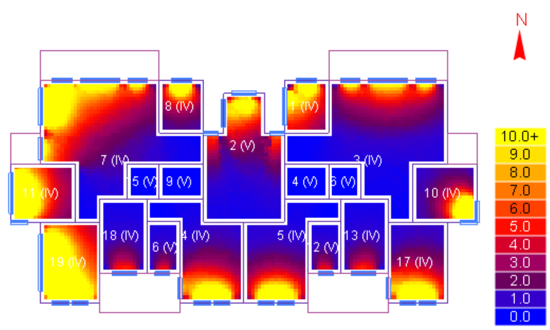
(e) west window/wall ratio 0.40



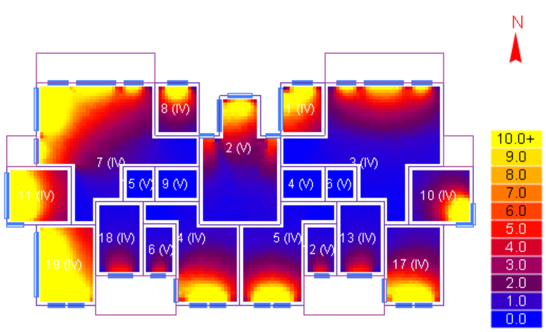
(f) west window/wall ratio 0.50



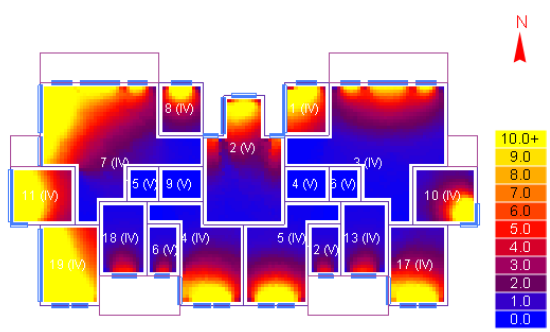
(g) west window/wall ratio 0.60



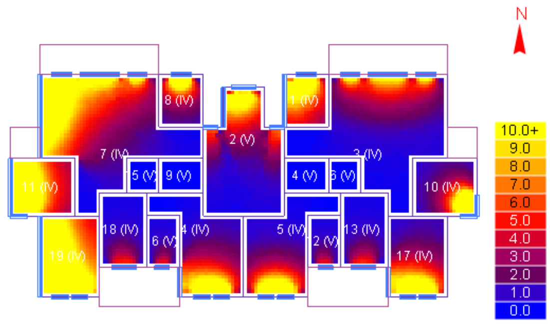
(h) west window/wall ratio 0.70



(i) west window/wall ratio 0.80



(j) west window/wall ratio 0.90



(k) west window/wall ratio 1.00

Figure 3.43 Lighting coefficient distribution of west rooms (with change of window width)

Source: Author

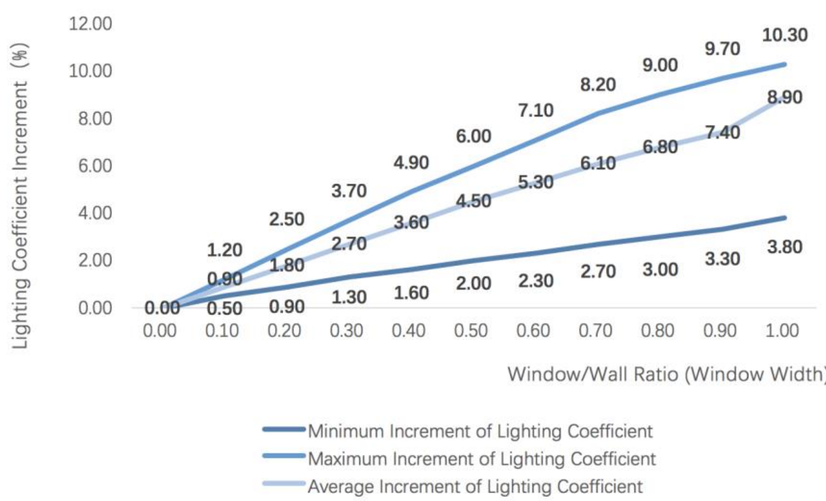


Figure 3.44 Lighting coefficient increments of west rooms caused by west window/wall ratio (window width)

Source: Author

Combining with the lighting coefficient distribution of west rooms and the data from lighting simulation report, the average lighting coefficient of each room in the west rooms is obtained. As shown in Figure 3.44, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window width) at 0.00. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the west window/wall ratio (window width); according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window width) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the west window/wall ratio (window width).

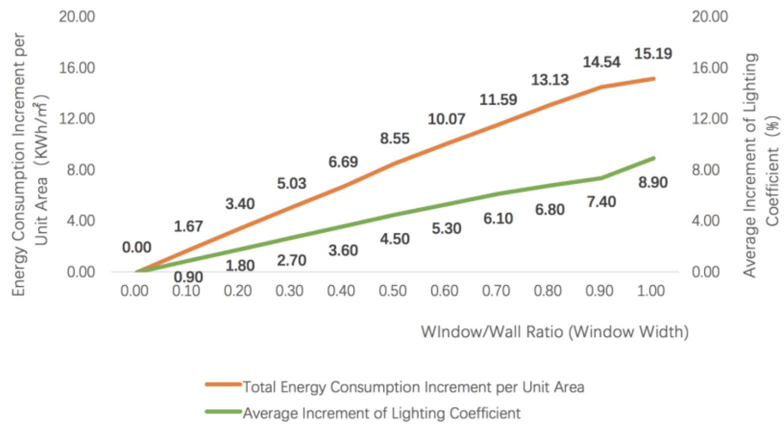


Figure 3.45 Increments of lighting coefficient and total energy consumption caused by west window/wall ratio (window width)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient is reflected in the same chart (Figure 3.45), which shows the relationships between the west window/wall ratio (window width), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The total situation shares a lot in common with the east counterpart.

Table 3.14 The relationship between simulated energy consumption in use phase and west window/wall ratio (window height) (KWh/m^2)

Windowsill Height 0.00m	Window Width as West Exterior Wall Width					Others Parameters as Reference Model					
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	0.97	1.93	2.91	3.86	4.92	5.87	6.82	7.75	8.69	9.18
Annual Heating Energy Increment	0.00	0.65	1.33	1.99	2.61	3.39	4.02	4.61	5.19	5.76	6.02
Annual Total Energy Increment	0.00	1.62	3.26	4.90	6.47	8.31	9.90	11.43	12.95	14.45	15.19

Source: Author

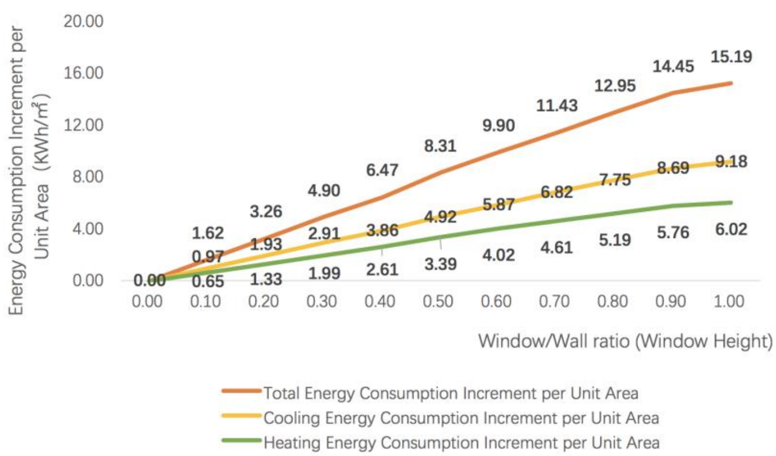
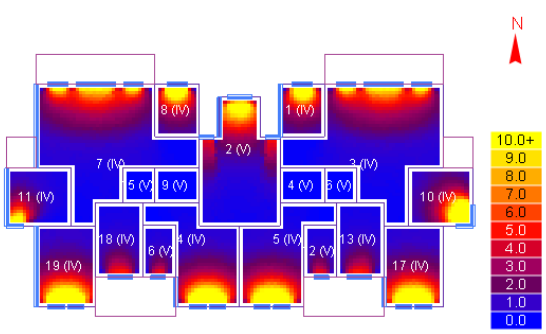


Figure 3.46 Relationship between simulated energy consumption in use phase and west window/wall ratio (window height)

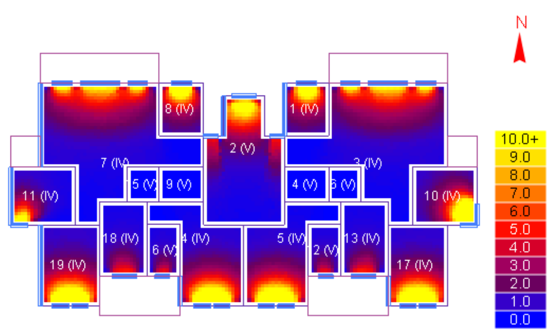
Source: Author

Table 3.14 and Figure 3.46 show the energy consumption changes in use phase caused by west window/wall ratio (window height). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the west window/wall ratio (window height) while the other parameters staying the same; the change of total energy consumption per unit area shows a direct positive correlation with the increase of the west window/wall ratio.

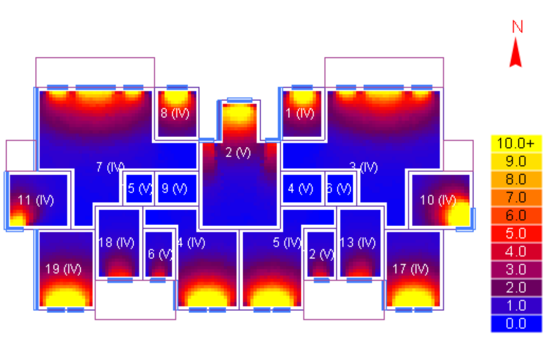
Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different west window/wall ratio (window height) were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.47).



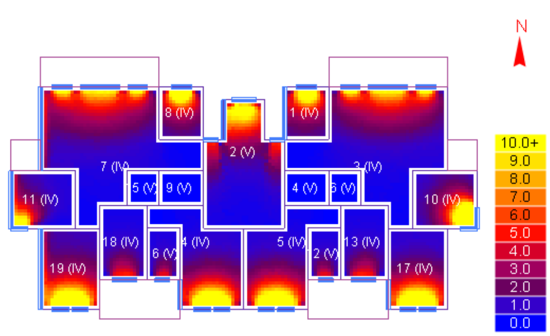
(a) west window/wall ratio 0.00



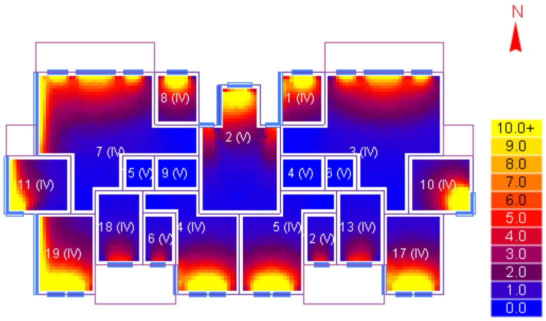
(b) west window/wall ratio 0.10



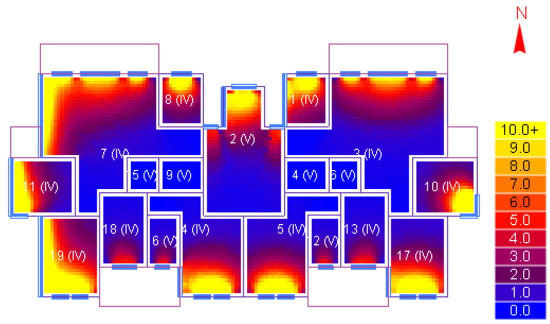
(c) west window/wall ratio 0.20



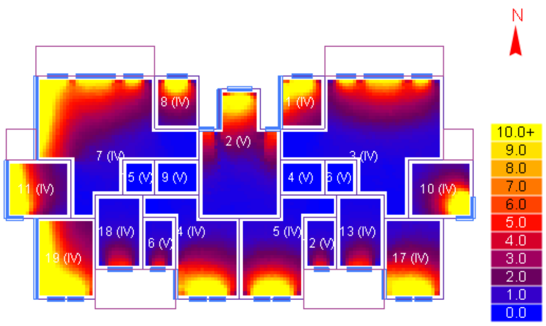
(d) west window/wall ratio 0.30



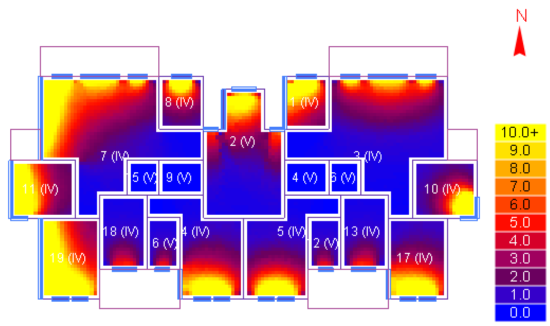
(e) west window/wall ratio 0.40



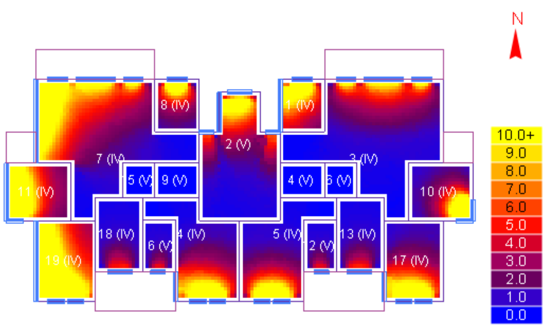
(f) west window/wall ratio 0.50



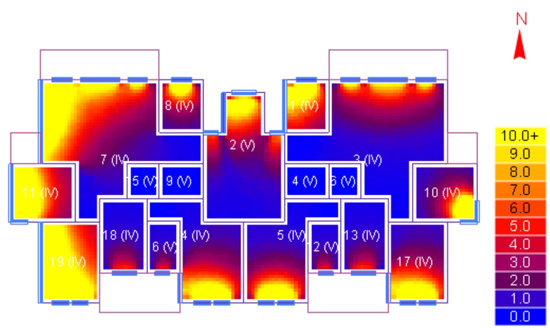
(g) west window/wall ratio 0.60



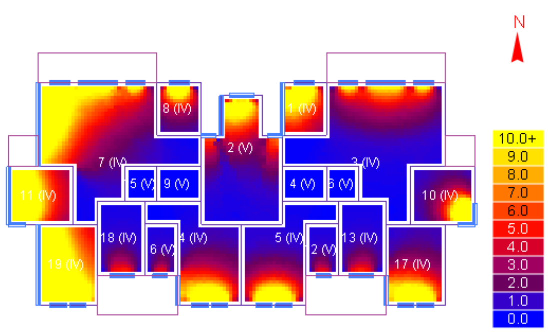
(h) west window/wall ratio 0.70



(i) west window/wall ratio 0.80



(j) west window/wall ratio 0.90



(k) west window/wall ratio 1.00

Figure 3.47 Lighting coefficient distribution of west rooms (with change of window height)

Source: Author

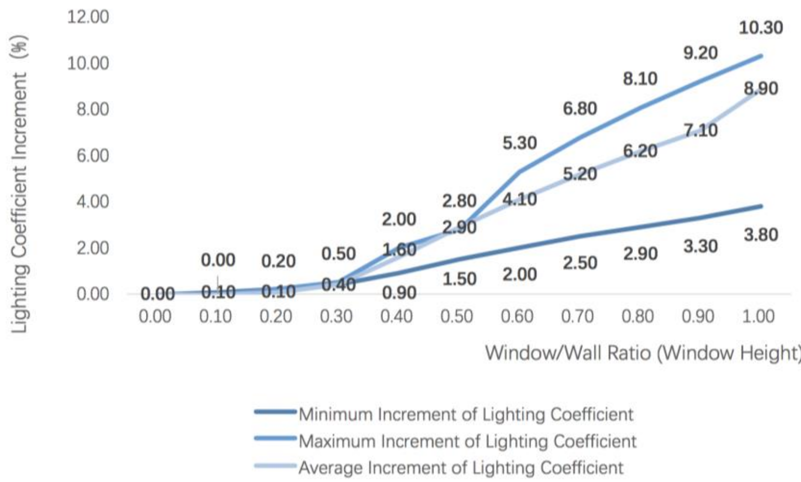


Figure 3.48 Lighting coefficient increments of west rooms caused by west window/wall ratio (window height)

Source: Author

Combining with the lighting coefficient distribution of west rooms and the data from lighting simulation report, the average lighting coefficient of each room in the west rooms is obtained. As shown in Figure 3.48, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window height) at 0.00. Similar with the other counterparts, the lighting coefficient increases with the increment of the west window/wall ratio (window height) when the ratio is beyond 0.30; the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window height) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the west window/wall ratio (window height).

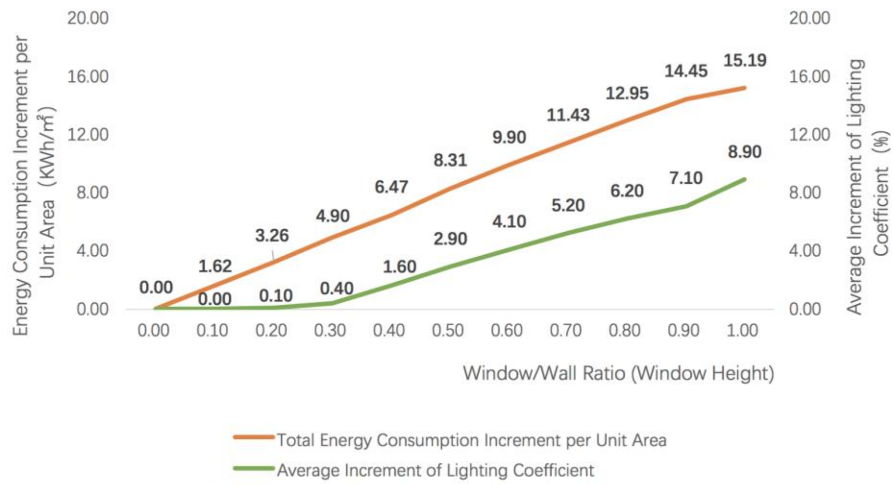


Figure 3.49 Increments of lighting coefficient and total energy consumption caused by west window/wall ratio (window height)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.49), which shows the relationships between the west window/wall ratio (window height), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way when the ratio is beyond 0.30 while the trend is not obvious when it is below 0.30.

(8) Simulation results of north window/wall ratio

Table 3.15 The relationship between simulated energy consumption in use phase and north window/wall ratio (window width) (KWh/m^2)

Windowsill Height 0.00m	Window height as Floor Height.	Others Parameters as Reference Model									
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	-0.59	-0.53	-0.45	-0.37	-0.24	-0.11	0.07	0.20	0.48	0.53
Annual Heating Energy Increment	0.00	1.03	2.02	2.98	3.89	4.78	5.66	6.5	7.33	8.18	8.60
Annual Total Energy Increment	0.00	0.44	1.49	2.53	3.52	4.53	5.55	6.57	7.53	8.67	9.13

Source: Author

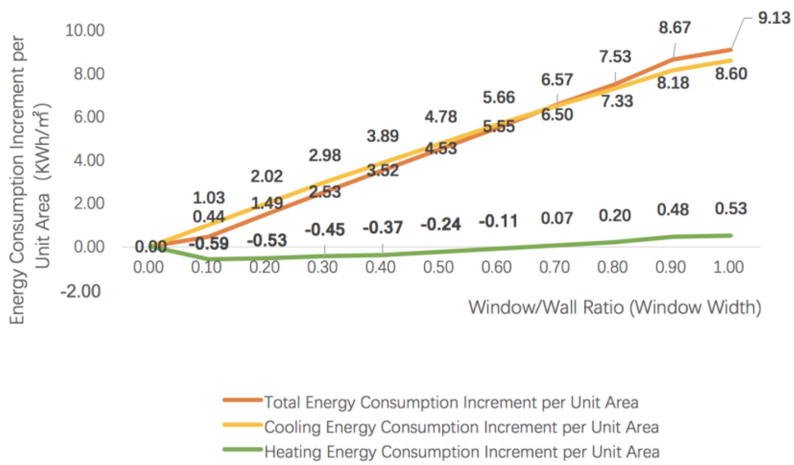
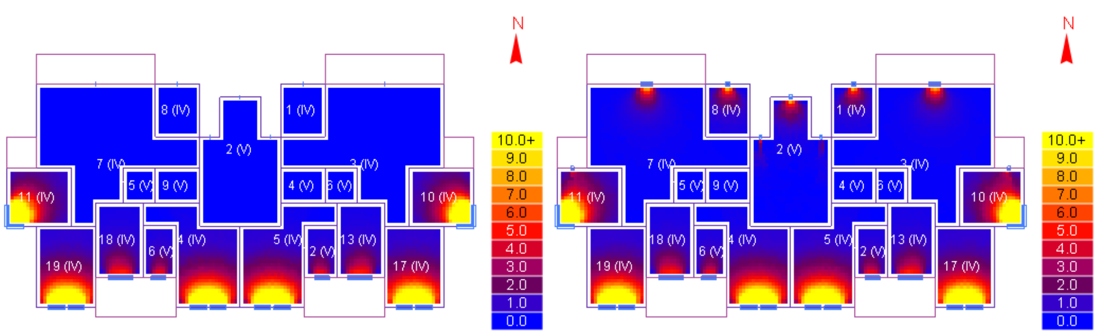


Figure 3.50 Relationship between simulated energy consumption in use phase and north window/wall ratio (window width)

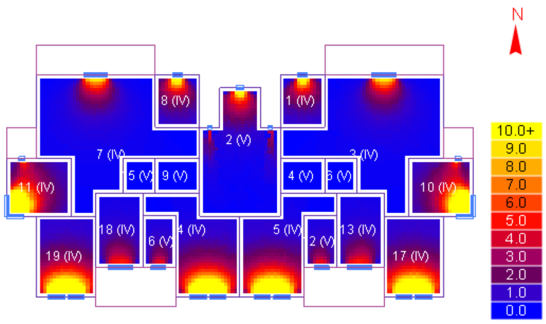
Source: Author

Table 3.15 and Figure 3.50 show the energy consumption changes in use phase caused by north window/wall ratio (window width). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the north window/wall ratio (window width) while the other parameters staying the same. However, the heating energy consumption shows a sudden drop when the ratio changes from 0.00 to 0.10 and its growing rate is much slower than the other ones. Overall, the change of total energy consumption per unit area shows a direct positive correlation with the increase of the north window/wall ratio (window width), the maximum incremental value is 9.13KWh/m^2 when the window/wall ratio is 1.00, much less comparing to the other counterparts.

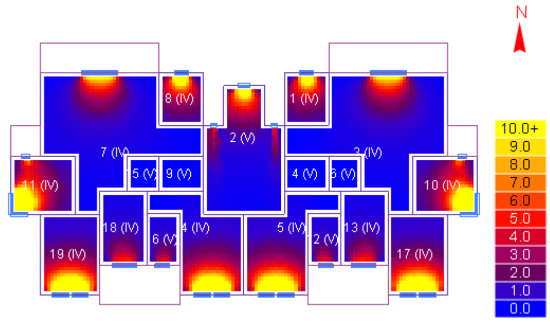
Then the lighting simulation was conducted for the corresponding models respectively. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.51).



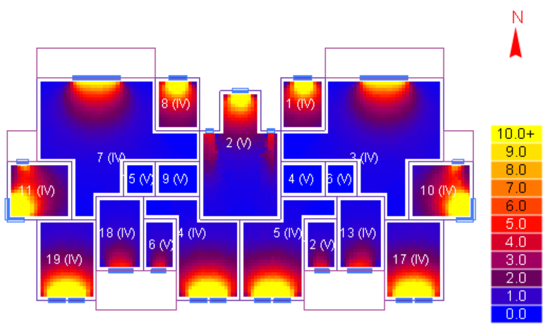
(a) north window/wall ratio 0.00 (b) north window/wall ratio 0.10



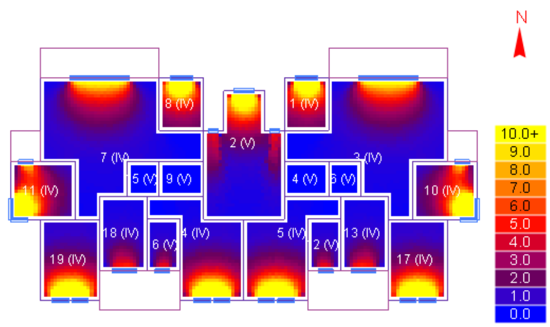
(c) north window/wall ratio 0.20



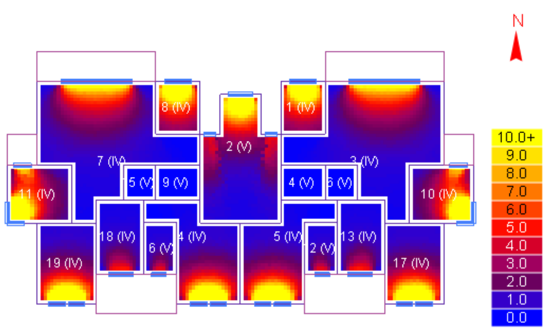
(d) north window/wall ratio 0.30



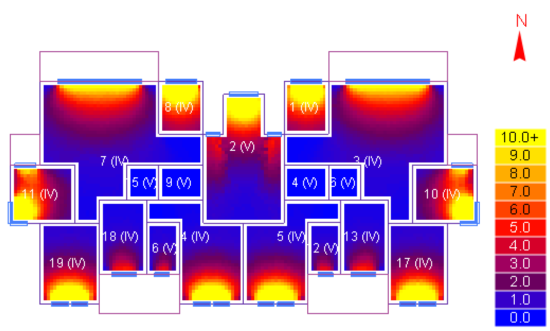
(e) north window/wall ratio 0.40



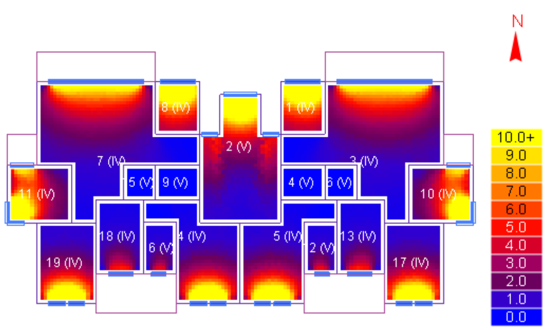
(f) north window/wall ratio 0.50



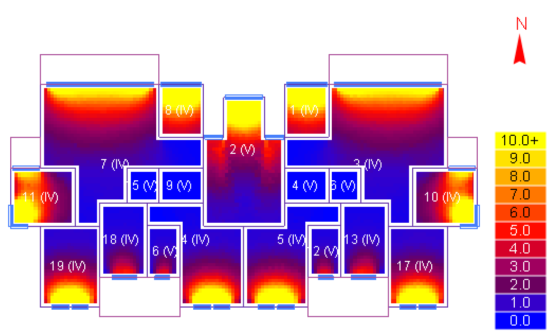
(g) north window/wall ratio 0.60



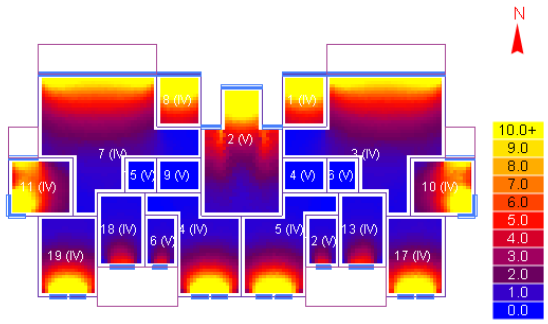
(h) north window/wall ratio 0.70



(i) north window/wall ratio 0.80



(j) north window/wall ratio 0.90



(k) north window/wall ratio 1.00

Figure 3.51 Lighting coefficient distribution of north rooms (with change of window width)

Source: Author

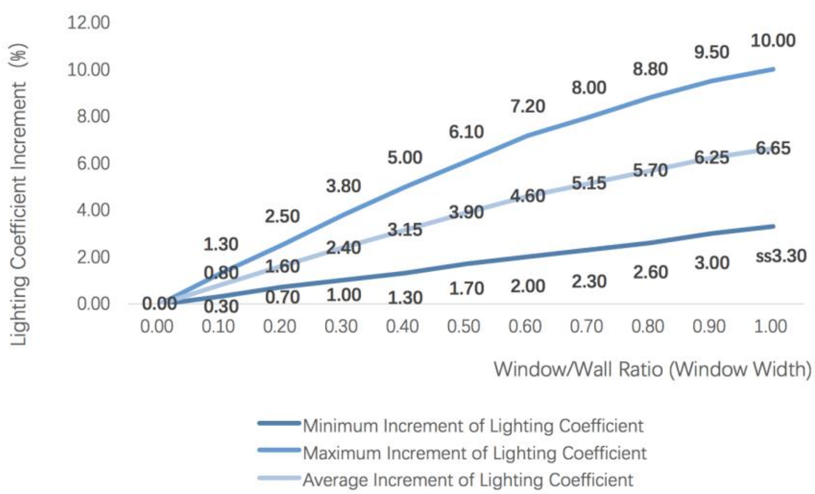


Figure 3.52 Lighting coefficient increments of north rooms caused by north window/wall ratio (window width)

Source: Author

Combining with the lighting coefficient distribution of north rooms and the data from lighting simulation report, the average lighting coefficient of each room in the north rooms is obtained. As shown in Figure 3.52, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window width) at 0.00. As can be directly seen from the trend of the curve, the lighting coefficient increases with the increment of the north window/wall ratio (window width); according to the graph of lighting coefficient distribution, the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window width) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the north window/wall ratio (window width).

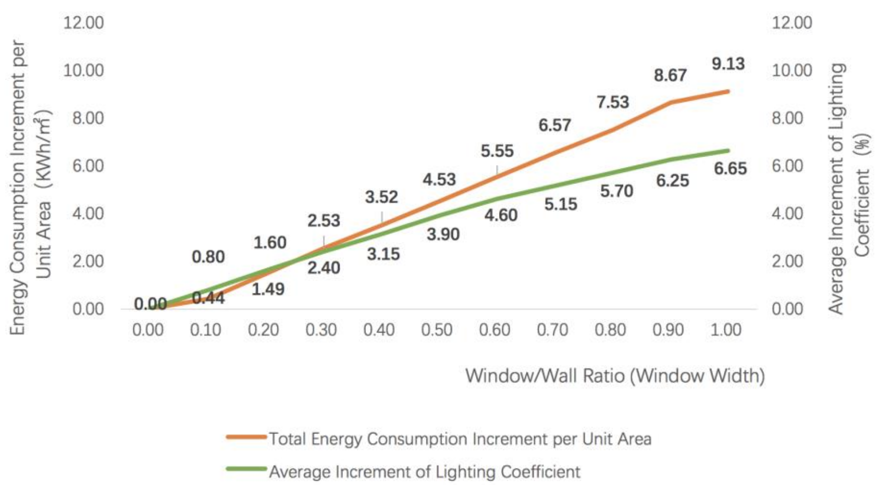


Figure 3.53 Increments of lighting coefficient and total energy consumption caused by north window/wall ratio (window width)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.53) in use phase.

Table 3.16 The relationship between simulated energy consumption in use phase and north window/wall ratio (window height) (KWh/m^2)

Windowsill Height 0.00m	Window Width as North Exterior Wall Width					Others Parameters as Reference Model					
Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
Annual Cooling Energy Increment	0.00	1.06	2.05	3.01	3.94	4.84	5.70	6.54	7.736	8.18	8.60
Annual Heating Energy Increment	0.00	-0.59	-0.54	-0.46	-0.38	-0.26	-0.12	0.06	0.25	0.48	0.53
Annual Total Energy Increment	0.00	0.47	1.51	2.55	3.56	4.58	5.58	6.60	7.62	8.66	9.13

Source: Author

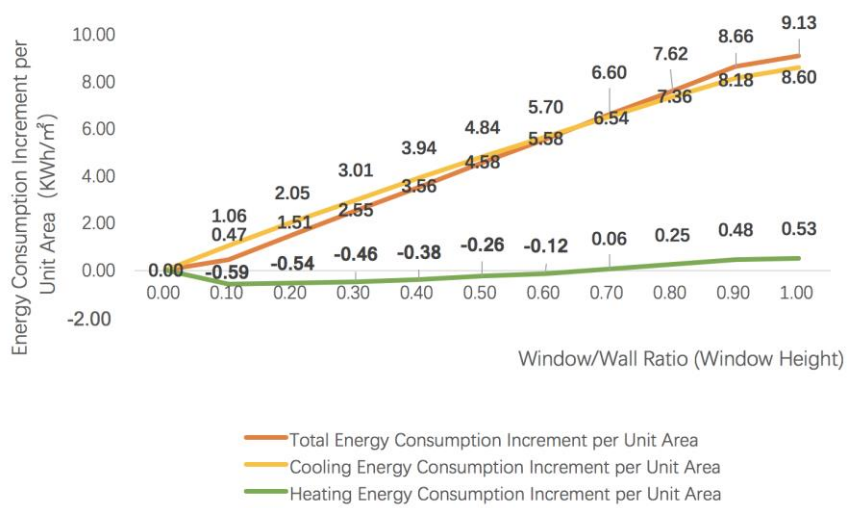
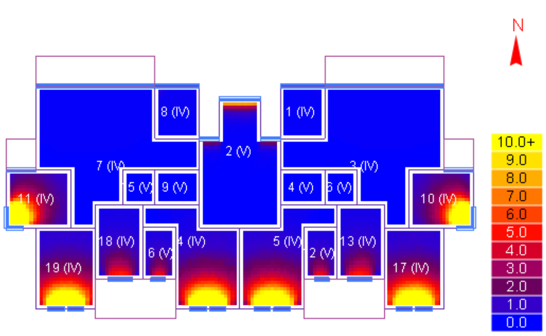


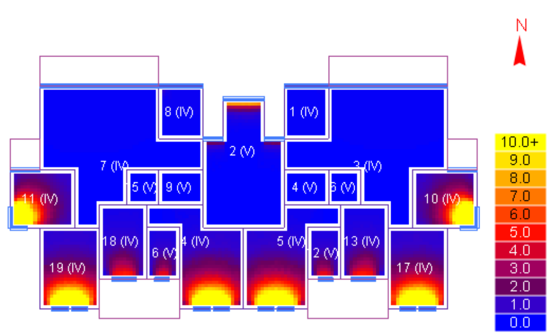
Figure 3.54 Relationship between simulated energy consumption in use phase and north window/wall ratio (window height)

Source: Author

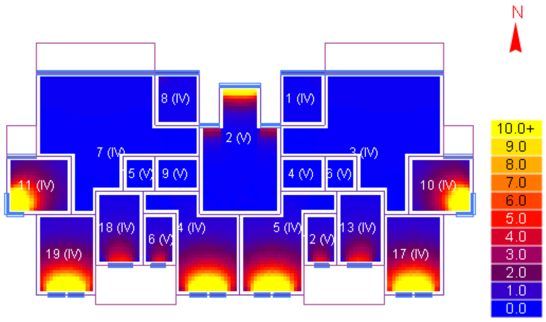
Table 3.16 and Figure 3.54 show the energy consumption changes in use phase caused by north window/wall ratio (window height). Likewise, the values at each point represents the energy consumption increment comparing to the reference energy consumption of the base model with a window/wall ratio at 0.00. It can be easily seen from the overall trend of the curve and the corresponding values of each parameter setting that the heating, cooling and overall energy consumption increases with the increment of the north window/wall ratio (window height) while the other parameters staying the same. However, the heating energy consumption shows a sudden drop when the ratio changes from 0.00 to 0.10 and its growing rate is much slower than the other ones. Overall, the change of total energy consumption per unit area shows a direct positive correlation with the increase of the north window/wall ratio (window width), the maximum incremental value is 9.13KWh/m^2 when the window/wall ratio is 1.00, much less comparing to the other counterparts. It can be considered that the north window/wall ratio has less influence on the energy consumption in use phase of residential building comparing to the other three counterparts.

Then the lighting simulation was conducted for the corresponding models respectively, and the illumination coefficient distribution figures of different north window/wall ratio (window height) were obtained. The figures of daylighting coefficient distribution in different color areas were represented by the different color areas to show the lighting conditions of each situation (Figure 3.55).

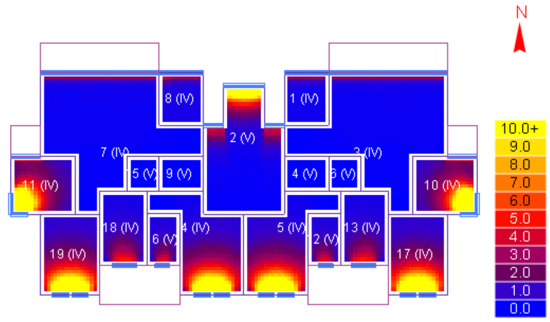




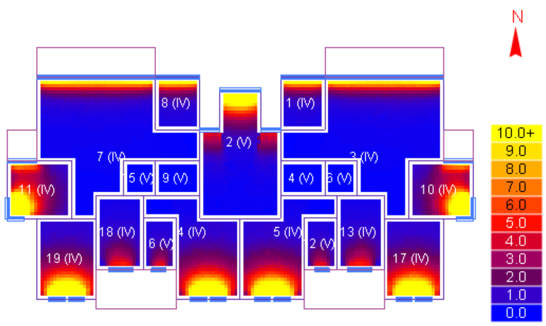
(a) north window/wall ratio 0.00 (b) north window/wall ratio 0.10



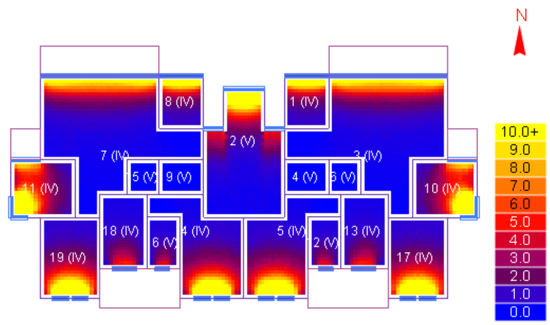
(c) north window/wall ratio 0.20



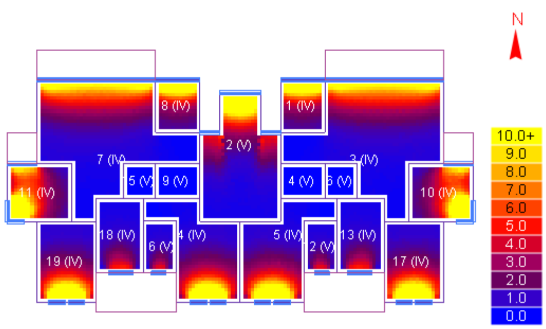
(d) north window/wall ratio 0.30



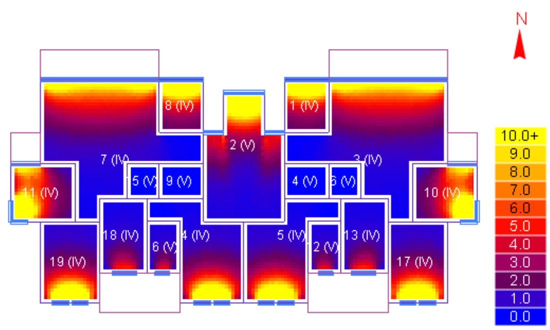
(e) north window/wall ratio 0.40



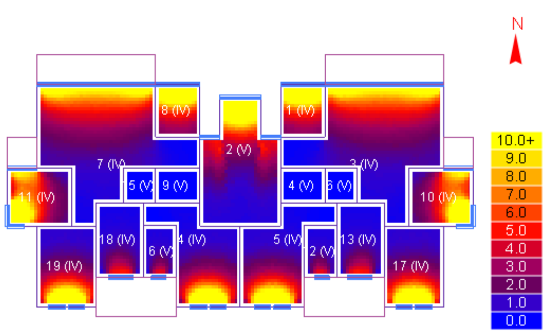
(f) north window/wall ratio 0.50



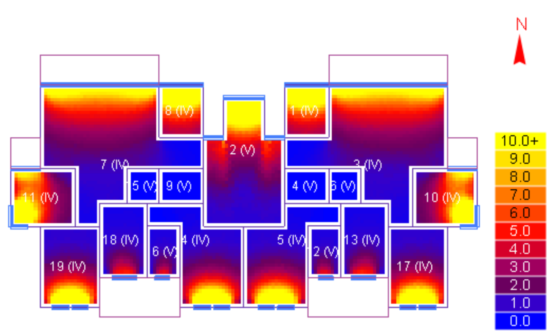
(g) north window/wall ratio 0.60



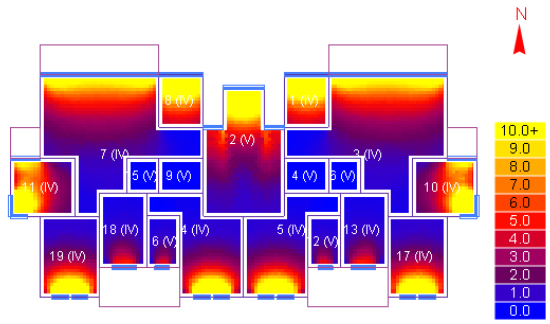
(h) north window/wall ratio 0.70



(i) north window/wall ratio 0.80



(j) north window/wall ratio 0.90



(k) north window/wall ratio 1.00

Figure 3.55 Lighting coefficient distribution of north rooms (with change of window height)

Source: Author

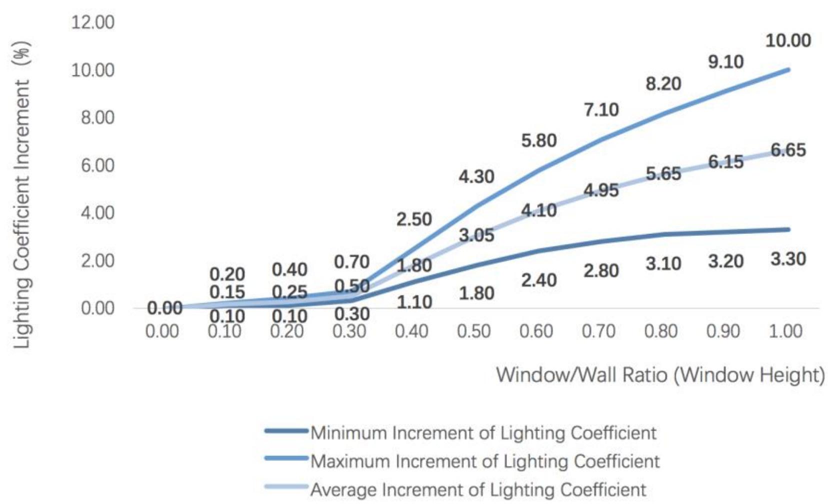


Figure 3.56 Lighting coefficient increments of north rooms caused by north window/wall ratio (window height)

Source: Author

Combining with the lighting coefficient distribution of north rooms and the data from lighting simulation report, the average lighting coefficient of each room in the north rooms is obtained. As shown in Figure 3.56, the values at each point represents the lighting coefficient increment comparing to the corresponding part of the base model with a window/wall ratio (window height) at 0.00. Similar with the other counterparts, the lighting coefficient increases with the increment of the north window/wall ratio (window height) when the ratio is beyond 0.30; the area of lighting coefficient distribution is also increasing. In summary, the average lighting coefficient of the room shows an increasing trend when window/wall ratio (window height) increases, with the total lighting area increasing and the evenness of the lighting condition improving as well, it can be considered that the lighting conditions improves with the increment of the north window/wall ratio (window height).

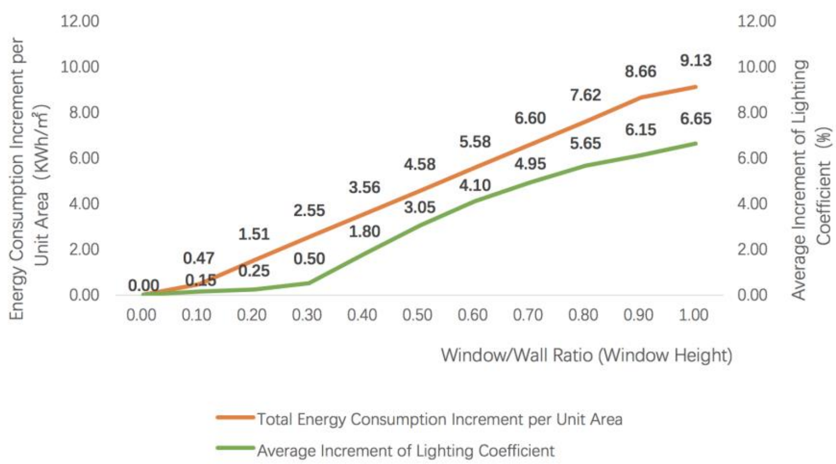


Figure 3.57 Increments of lighting coefficient and total energy consumption caused by north window/wall ratio (window height)

Source: Author

The average incremental change of total energy consumption per unit area and lighting coefficient are reflected in the same chart (Figure 3.57), which shows the relationships between the north window/wall ratio (window height), the corresponding changes of energy consumption and the lighting coefficient distribution in use phase. The overall lighting area and lighting evenness of the room can be considered increased with the energy consumption going up all the way when the ratio is beyond 0.30 while the trend is not obvious when it is below 0.30. The growing rates of the two curves are quite close, which is different from the other counterparts, showing a potential possibility of improving the lighting coefficient without causing so much energy consumption like the other 3 counterparts.

After completing the simulation and related analysis of lighting and energy consumption changes caused by the different parameters and variables, the energy consumption results of each parameter are obtained, which will become the basis of the coming estimation process of carbon emission.

3.3.4 Estimated Carbon Emission in Use Phase

In the last section, the energy consumption data of the windowsill height and the window/wall ratio is obtained. According to the national grid emission factors released by the National Climate Change Agency of the National Development and Reform Commission, the carbon emission can be calculated by bringing the energy consumption into the following formula 3.3, 3.4:

$$\Delta E_U = EF_E \times \Delta C_E \tag{3.3}$$

$$EF_E = (EF_{grid, OM, y} + EF_{grid, BM, y}) /2 \tag{3.4}$$

ΔE_U represents the carbon emission change of residential building in use phase ($kgCO_2eq$);

EF_E represents the grid baseline emission factor in Shanghai area ($kgCO_2eq/KWh$);

ΔC_E represents the annual total energy consumption difference of residential building in use phase (KWh);

$EF_{grid, OM, y}$ represents the electricity marginal emission factor of the regional grid ($kgCO_2eq/KWh$);

$EF_{grid, BM, y}$ represents the capacity marginal emission factor of the regional grid ($kgCO_2eq/KWh$).

Table 3.17 Regional power grid division

Region	Provinces and Cities
East	Shanghai, Jiangsu Province, Zhejiang Province, Anhui Province, Fujian Province

Source: China Clean Development Mechanism Net

Table 3.18 Regional grid emission factor of 2015

Regional Grid	$EF_{grid,OM,y}$ ($kgCO_2eq/KWh$)	$EF_{grid,BM,y}$ ($kgCO_2eq/KWh$)
East	0.8112	0.5945

Source: China Climate Change Agency of NDRC

As can be seen from the tables above, Shanghai belongs to the east regional grid division. According to the data from the tables, the EF_E of east regional grid is 0.7029

($kgCO_2eq$/KWh). With the energy consumption data taken into the formula 3.3 respectively, the carbon emission data is calculated. The window/wall ratio data can be considered as an average value of the counterpart of width and height. The outcomes are listed in the following tables (Table 3.19 and Table 3.20).

Table 3.19 Annual increment of carbon emissions caused by windowsill height in use phase ($kgCO_2eq/m^2$)

Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
East	0.0000	0.0006	0.0014	0.0039	0.0078	0.0116	0.0163	0.0167
South	0.0000	0.0057	0.0084	0.0106	0.0120	0.0127	0.0127	0.0159
West	0.0000	0.0039	0.0082	0.0149	0.0227	0.0331	0.0421	0.0404
North	0.0000	0.0086	0.0176	0.0255	0.0282	0.0306	0.0331	0.0363

Source: Author

Table 3.20 Annual increment of carbon emissions caused by window/wall ratio in use phase ($kgCO_2eq/m^2$)

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East	0.00	1.10	2.27	3.76	4.90	6.24	7.43	8.53	9.58	10.72	11.27
South	0.00	0.78	1.77	2.75	4.02	6.02	7.71	9.96	11.83	14.00	15.24
West	0.00	1.16	2.34	3.49	4.63	5.93	7.02	8.09	9.17	10.19	10.68
North	0.00	0.32	1.06	1.79	2.48	3.20	3.91	4.63	5.32	6.09	6.42

Source: Author

Carbon emission changes caused by different windowsill heights and window/wall ratios can be directly seen from the tables above.

3.4 Carbon Emission Changes Caused by Residential Natural Lighting Design in Materialization and Demolition Phase

Each residential building needs to go through a long process of materialization, from production, manufacturing, processing and transportation of different materials and components; assembling and construction; at last, the demolition phase, which includes taking care of the remaining, recycling and so on. All of these processes are accompanied by the carbon emissions. This section will focus on calculating the carbon emission changes in the materialization and demolition phases of residential buildings caused by lighting design.

3.4.1 Changes in the Amount of Envelope Structures and Related Carbon Emission Factors

Residential buildings, like most other types of buildings, consist of envelop structure and supporting structure. In previous software simulations, windowsill height and window/wall ratios were adjusted based on the reference model with other parameters staying unchanged, thus, it can be regarded as no change in the supporting structure. Therefore, the carbon emissions in the materialization and demolition phases are reflected in the changes of the envelope structure.

It can be considered that changing the windowsill height does not have influence on material change. While changing the window/wall ratio results in a change of the window area and wall area due to the total area is a fixed constant for a building. Due to the fact that the materialization and demolition processes of different envelope structures are also different, the changes of the amount of different envelope structures are the main factors that change the carbon emissions of residential buildings in these phases. The envelope materials of the reference residential building are concrete block and insulated aluminum alloy window frame with double low-e hollow glazing. Thus, the carbon emission caused by window/wall ratio can be calculated by applying the formula 3.5, 3.6 listed below.

$$\Delta E_{MG} = \Delta R_O \times S_O \times C_{MG} \tag{3.5}$$

$$\Delta E_{MC} = (1-\Delta R_O) \times S_O \times C_{MC} \tag{3.6}$$

ΔR_O represents the window-wall ratio;

S_O represents the envelope area of each orientation (m^2);

ΔC_{MG} is the reference value of carbon emission per unit area ($kgCO_2eq/m^2$) per unit area of insulated aluminum alloy window frame with double low-e hollow glazing;

ΔC_{MC} is the carbon emission per unit area of concrete block wall ($kgCO_2eq/m^2$).

The reference values for the materials used as envelope structure are obtained from the database which is widely used in the United States, the Athena Eco Calculator for Residential Assemblies, as mentioned in Chapter 2. This database collects a large number of homes in the United States, after conducting a huge amount of calculations and material statistics, a systematic database for carbon emission calculation is completed. The following calculation of the materialization and demolition phase will be conducted on a basis of this database.

Figure 3.58 Carbon emission factor of wall per unit area in the Athena database

Source: Athena Eco Calculator for Residential Assemblies

Figure 3.59 Carbon emission factor of window per unit area in the Athena database

Source: Athena Eco Calculator for Residential Assemblies

As shown in the figures listed above, it can be seen that the closet wall material is the No.3 type wall (which is concrete block, 2 coat stucco over porous surface, R5 XPS continuous insulation). Its GWP value is 7.07kgCO_2eq/ft^2, which converted to a metric unit is 78.56kgCO_2eq/m^2; similarly, the GWP of insulated aluminum alloy window frame with double low-e hollow glazing (aluminum operable low-e double glazing) is 67.63kgCO_2eq/ft^2, which converted to metric units is 751.44kgCO_2eq/m^2.

3.4.2 Estimation of Carbon Emission Change in Materialization and Demolition Phase

$$\Delta E_M = (\Delta E_{MG} + \Delta E_{MC}) / S_C \tag{3.7}$$

ΔE_M represents the change of carbon emission per unit area ($kgCO_2eq/m^2$) caused by envelope structure change in materialization and demolition phase;

ΔE_{MG} represents the change of carbon emission caused by the area change of aluminum operable low-e double glazing ($kgCO_2eq$);

ΔE_{MC} represents the change in carbon emissions caused by concrete block walls with XPS insulation ($kgCO_2eq$);

S_C represents the total floor area (m^2).

Taking the related parameters into formula 3.5, 3.6 and 3.7 respectively for calculation, the outcomes are listed below (Table 3.21).

Table 3.21 Increment of carbon emissions caused by window/wall ratio in materialization and demolition phase ($kgCO_2eq/m^2$)

Total Floor Area 3442.17m^2 East/West Surface Area 799.22m^2 South/North Surface Area 967.98m^2

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East	0.00	15.62	31.25	46.87	62.49	78.12	93.74	109.36	124.99	140.61	156.23
South	0.00	18.92	37.85	56.77	75.69	94.61	113.54	132.46	151.38	170.30	189.22
West	0.00	15.62	31.25	46.87	62.49	78.12	93.74	109.36	124.99	140.61	156.23
North	0.00	18.92	37.85	56.77	75.69	94.61	113.54	132.46	151.38	170.30	189.22

Source: Author

As mentioned before, the adjustment of the windowsill height does not affect the amount of material used for the building envelope. Thus, it can be considered that different settings of windowsill height do not cause any carbon emission changes in materialization and demolition phase.

3.5 Carbon Emission Changes Caused by Residential Natural Lighting Design in Whole Life Cycle

According to the formula 3.1 proposed in previous chapter, the carbon emission changes in whole life cycle can be calculated by taking all results gathered above in materialization phase, use phase, and demolition phase. To simplify the process, the use phase is calculated as 50 years. The final results are listed as below (Table 3.22 and 3.23).

Table 3.22 Increment of carbon emissions caused by windowsill height in whole life cycle (50 years) ($kgCO_2eq/m^2$)

Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
East	0.00	0.03	0.07	0.19	0.39	0.58	0.82	0.84
South	0.00	0.29	0.42	0.53	0.60	0.63	0.63	0.80
West	0.00	0.19	0.41	0.75	1.13	1.65	2.10	2.02
North	0.00	0.43	0.88	1.28	1.41	1.53	1.65	1.82

Source: Author

Table 3.23 Increment of carbon emissions caused by window/wall ratio in whole life cycle (50 years) ($kgCO_2eq/m^2$)

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East	0.00	70.62	144.75	234.87	307.49	390.12	465.24	535.86	603.99	676.61	719.73
South	0.00	57.92	126.35	194.27	276.69	395.61	499.04	630.46	742.88	870.30	951.22
West	0.00	73.62	148.25	221.37	293.99	374.62	444.74	513.86	583.49	650.11	690.23
North	0.00	34.92	90.85	146.27	199.69	254.61	309.04	363.96	417.38	474.80	510.22

Source: Author

As can be seen from the chart above, the carbon emission increment caused by window/wall ratio are significantly more than the counterpart of windowsill. Therefore, the window/wall ratio may be the most potential aspect that should be pay more attention to when dealing with carbon emission issues of residential buildings.

Table 3.24 Lighting coefficient increment caused by windowsill height (%)

Windowsill Height（m）	0.00	0.30	0.60	0.90	1.20	1.50	1.80	2.10
East	0.00	1.26	2.53	3.33	3.26	2.76	2.43	2.10
South	0.00	1.06	1.68	2.41	2.50	1.50	1.18	0.95
West	0.00	1.10	2.40	3.33	4.00	2.87	2.50	2.13
North	0.00	1.08	2.04	2.87	2.56	2.18	1.84	1.54

Source: Author

Table 3.25 Lighting coefficient increment caused by window/wall ratio (width) (%)

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East	0.00	0.90	1.90	2.80	3.70	4.60	5.50	6.30	7.00	7.60	8.10
South	0.00	0.58	1.22	1.85	2.45	3.00	3.60	4.10	4.50	4.90	5.20
West	0.00	0.90	1.80	2.70	3.60	4.50	5.30	6.10	6.80	7.40	8.90
North	0.00	0.80	1.60	2.40	3.15	3.90	4.60	5.15	5.70	6.25	6.65

Source: Author

Table 3.26 Lighting coefficient increment caused by window/wall ratio (height) (%)

Window/Wall Ratio	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
East	0.00	0.30	0.20	0.40	2.20	3.20	4.40	5.40	6.40	7.30	8.10
South	0.00	0.05	0.13	0.40	1.48	2.43	3.20	3.80	4.30	4.80	5.20
West	0.00	0.00	0.10	0.40	1.60	2.90	4.10	5.20	6.20	7.10	8.90
North	0.00	0.15	0.25	0.50	1.80	3.05	4.10	4.95	5.65	6.15	6.65

Source: Author

On the other hand, the simulation results of lighting coefficient can be summarized in the following tables (Table 3.24, Table 3.25 and Table 3.26).

CHAPTER 4 EMPIRICAL RESEARCH BASED ON BUILT RESIDENTIAL PROJECTS, SHANGHAI

4.1 Basic Information of Empirical projects

In the previous chapter, the data of the lighting coefficient distribution and energy consumption of each simulation model are obtained. Given the results are obtained under the theoretical background bases on the ideal situation, this chapter, empirical study will combine those results with real data and circumstances, which includes actual energy consumption data and the evaluation of the residents, to make the research outcomes more reliable.

The basic information of the empirical research projects, 2 different residential building with similarities, are summarized as below (Table 4.1 and Table 4.2). The simulation reference model is built based on the information of the project 1. These two projects share a lot in common, like the window types they use, the floor height, the total number of units, total floor area, building shape coefficient and construction era and so on. Therefore, these two projects can provide a certain comparability and some scientific value as empirical research objects.

Table 4.1 Basic information of project 1

Location	Shanghai（31°N，121°E）
Construction Year	2009
Orientation	South
Building Shape Coefficient	0.39
Building Area	3442.17 m^2
Unit Area	143.40 m^2
Number of Units	24
Floor Height	3.0 m
Exterior Wall (from Outside to Inside)	Concrete block, 2 coat stucco over porous surface, R5 XPS continuous insulation
Window	Aluminum operable low-e double glazing
Window/Wall ratio	East 0.05；South 0.35；West 0.05；North 0.35
Windowsill Height	0.60 m

Source: Author

Table 4.2 Basic information of project 2

Location	Shanghai（31°N，121°E）
Construction Year	2012
Orientation	South
Building Shape Coefficient	0.40
Building Area	3081.27 m^2
Unit Area	128.40 m^2
Number of Units	24
Floor Height	2.90 m
Exterior Wall (from Outside to Inside)	Concrete block, 2 coat stucco over porous surface, R5 XPS continuous insulation
Window	Aluminum operable low-e double glazing
Window/Wall ratio	East 0.04；South 0.19；West 0.02；North 0.13
Windowsill Height	0.90 m

Source: Author

4.2 Energy Consumption Calculation Based on Actual Electricity Consumption of Empirical Projects

Under the support of Tongji University and National Science Foundation of China, the anonymous actual electricity consumption data of 2015 of the empirical residential buildings, which mentioned above were obtained through the cooperation with the regional national grid. After collecting, summarizing and analyzing the rare data, the average electricity consumption of each household in the empirical projects are gathered as follows (Table 4.3 and Table 4.4).

Table 4.3 Average Electricity Consumption of Project 1

Month	1	2	3	4	5	6	7	8	9	10	11	12
Peak	158.59	169.29	142.34	136.85	103.79	101.79	107.84	154.77	172.31	111.88	105.33	122.86
Valley	70.56	73.49	61.78	59.52	42.45	41.80	46.73	73.79	90.03	49.19	42.09	49.58
Total	229.15	242.79	204.12	196.37	146.24	143.59	154.58	228.56	262.34	161.08	147.43	172.44

Source: Author

Table 4.4 Average Electricity Consumption of Project 2

Month	1	2	3	4	5	6	7	8	9	10	11	12
Peak	149.35	156.72	131.24	129.45	96.09	92.51	95.12	141.94	154.52	95.38	94.15	109.57
Valley	49.84	53.05	46.24	42.86	33.87	34.94	38.91	70.41	81.86	40.95	33.86	36.82
Total	199.20	209.77	177.48	172.30	129.95	127.44	134.04	212.35	236.37	136.33	128.01	146.39

Source: Author

After a thorough analysis of the average monthly electricity consumption of each household in both empirical projects, it is obvious that the numbers show a pattern - the average total electricity costs in January, February, March, August, September in both projects are significantly higher than those in other months. Combined with the life experience, August and September are the hottest summer months in Shanghai, while the other months just mentioned before are the coldest months. The daily household appliances can be considered not seasonally affected except for cooling and heating equipment. Therefore, it can be generally considered that the difference between the average monthly electricity consumption of months which the numbers increased sharply and counterparts of the other months in the same year was due to the operation of domestic cooling and heating equipment. To be more specific, the energy consumption per household per year of cooling equipment are the numbers of months with monthly average consumption showing a significant increase in summer multiply the difference between these average electricity consumption numbers in summer and the average numbers in both spring and autumn. Similar, the annual energy consumption per household of heating equipment in each project are the numbers of months with monthly average consumption showing a significant increase in winter multiply the difference between these average electricity consumption numbers in winter and the average numbers in both spring and autumn. Then the annual consumption per unit area can be calculated by multiplying operating electricity consumption of each household cooling and heating equipment with the number of the households, then divided by the total area of their building area (Table 4.5).

Table 4.5 Annual energy consumption per unit area of projects （KWh/m^2）

Project	Cooling	Heating	Total	Household	Building Area	Cooling per Unit Area	Heating per Unit Area	Total per Unit Area
1	209.09	274.86	483.95	24	3442.17	1.46	1.92	3.37
2	207.29	270.37	477.66	24	3081.27	1.61	2.11	3.72

Source: Author

4.3 Questionnaire Survey of Empirical Projects

4.3.1 The Purpose of Questionnaire Survey

In order to obtain the accurate lighting evaluation of the empirical projects, the natural lighting evaluation questionnaire is designed and handed out to the residents living in the empirical projects in person and collected for further analysis.

The main purpose of this questionnaire survey is to use household evaluation as an indicator of actual residential natural lighting conditions, together with the actual energy consumption data to make a comparison study with the simulation study outcomes, aiming at make the whole research more solid.

4.3.2 Statistics of Questionnaire Survey

In order to ensure the accuracy of the sample and the reference values for this research, samples are selected from the households in the actual residential buildings which has been used as the reference model in previous simulation. Finally, 58 valid questionnaires are collected from the empirical project 1, and 53 valid questionnaires for the project 2.

The valid questionnaires collected above are organize, analyzed and a series comparative study is conduct to explore their results. In order to facilitate the conversion of subjective feelings of households into data, the subjective feelings of households for the evaluation of residential related indicators are converted into grading when the questionnaire results are statistically analyzed; and the grading for being very satisfied is a score of 5 and the grading for being very dissatisfied with a score of 1. Each evaluation between these two was recorded accordingly as 4, 3, 2 points. The final grading results are as follows (Figure 5.1, Figure 5.2 and Figure 5.3).

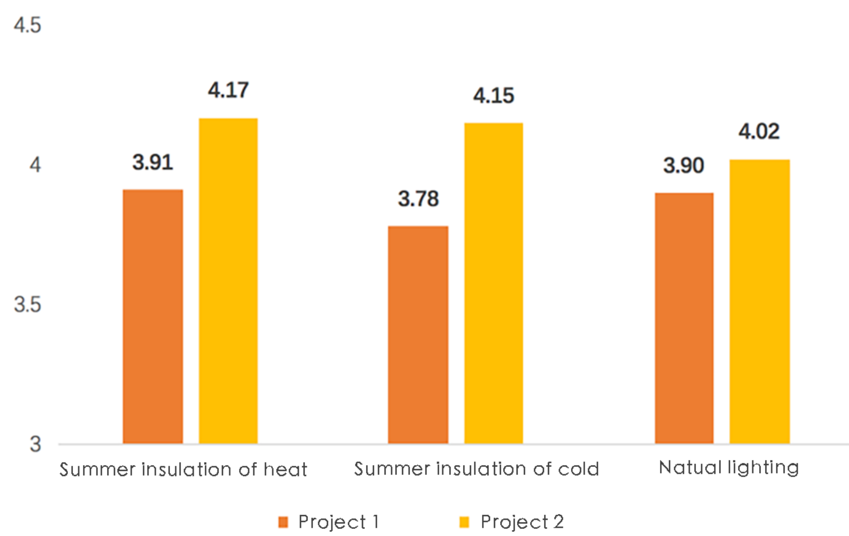


Figure 4.1 Grading of related residential indicators

Source: Author

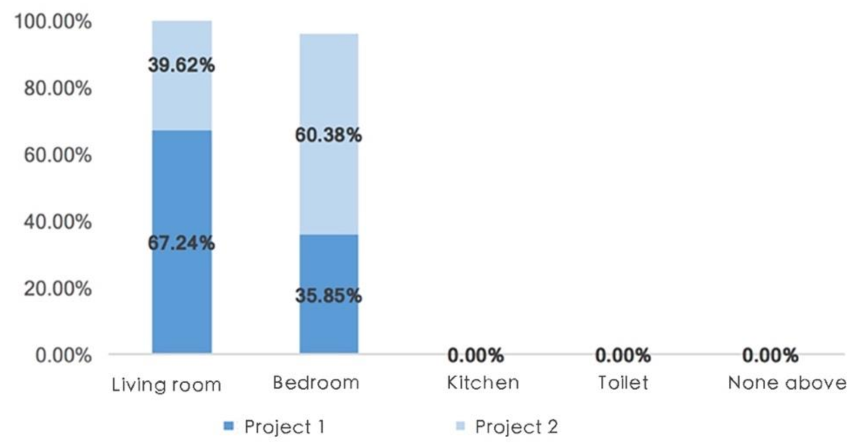


Figure 4.2 Rooms with most satisfaction

Source: Author

Figure 4.3 Rooms with least satisfaction

Source: Author

The following conclusions can be drawn from the statistical results of the questionnaire survey: project 2 has better ratings than project 1 in all indicators; in both of them, the rooms with the best lighting condition are the living rooms, followed by bedrooms in project 1 while the bedrooms, followed by living rooms in project 2; however, when it comes to the worst, 18.87% of the respondents choose the living room in project 2, whereas in project 1, they were 0; another important thing is all rooms share a higher percentage in dissatisfaction than project 1 does, except for the kitchen in this part; in the most unsatisfactory room selection, nearly 30% of the households of both projects vote to the bathroom; but amazingly, in Project 1, nearly 40% of households think that there is no unsatisfactory in their units for natural lighting, significantly higher than 11.32% in project 2. To sum up, it can be concluded that the ranking of natural lighting in each room in project 1 is sorted from high to low as the following. Living room > bedroom > kitchen > bathroom; similarly, the counterpart of project 2 is sorted as follows. Bedroom > living room > kitchen > bathroom.

4.4 A Comparison Study of Simulation and Empirical Findings

The above projects are modeled respectively according to their building information. In the meantime, simulations based on these two projects are conducted, and the energy consumption and natural lighting simulation results are obtained, which can be compared with the actual electricity consumption data and the corresponding household lighting evaluation ratings obtained in the previous two sections of this chapter for a comprehensive comparison study to find out link between simulation and actual circumstance, also can help to examine the accuracy of the simulation.

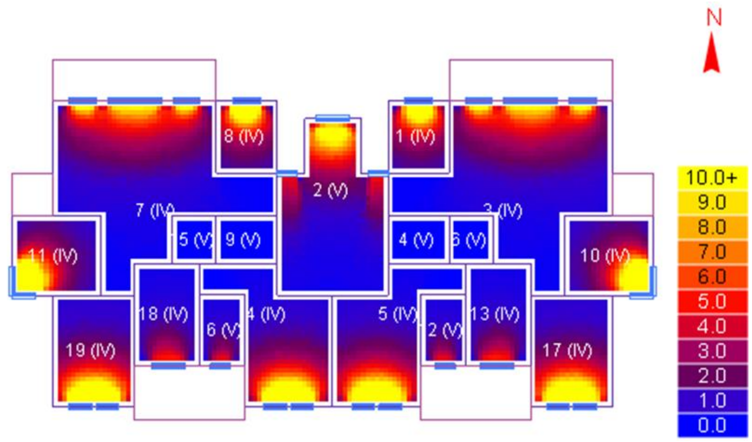


Figure 4.4 Lighting coefficient distribution of project 1

Source: Author

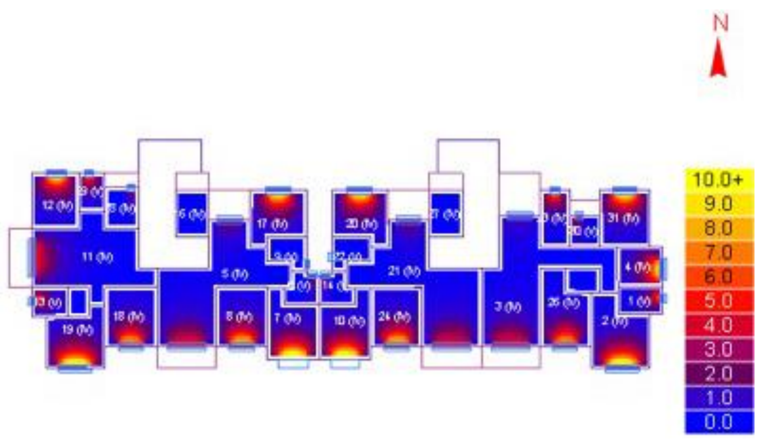


Figure 4.5 Lighting coefficient distribution of project 2

Source: Author

Table 4.6 Average lighting coefficient of projects（%）

Project	Living Room	Bedroom	Kitchen	Toilet	Average
1	1.90	4.30	4.60	1.40	3.05
2	0.70	2.10	0.40	1.20	1.05

Source: Author

Table 4.7 Annual energy consumption Simulation of Projects（KWh/m^2）

Project	Cooling	Heating	Total
1	21.65	36.23	57.89
2	17.66	43.30	60.96

Source: Author

Table 4.8 Relevant simulation and empirical data of projects

Project	Rating for Insulation of heat	Actual Energy Consumption of Cooling	Simulated Energy Consumption of Cooling	Rating for Insulation of Cold	Actual Energy Consumption of Heating	Simulated Energy Consumption of Heating	Actual Total Energy Consumption	Simulated Total Energy Consumption	Rating for Natural Lighting	Simulated Lighting Coefficient
1	3.91	1.46	21.65	3.78	1.92	36.23	3.37	57.89	3.90	3.05
2	4.17	1.61	17.66	4.15	2.11	43.30	3.72	60.96	4.02	1.10

Source: Author

Combined with the charts listed above, conclusions can be made as following. In terms of energy consumption, the gap of the values between actual energy consumption and the simulated energy consumption are still enormous, but the relative trends of empirical data and simulation are the same. For lighting part, though the lighting rating of project 1 is slightly lower than the counterpart of project 2, but as for the satisfaction of each room, project 1 overall significantly lead project 2, also confirmed the same trend as lighting simulation results - the lighting coefficient of project 1 is significantly higher than that of project 2.

The empirical data gives some support to the conclusions drawn from the simulation in the previous chapter from the perspective of actual circumstance. However, it also reflects the unavoidable limitations of simulation due to its idealization and theorization, which neglect many complex factors in real life. Thus, the next chapter will discuss more about what may be implement to this research.

CHAPTER 5 POTENTIAL OF CARBON EMISSION REDUCTION OF HOUSEHOLD BEHAVIOR AND RESIDENTIAL NATURAL LIGHTING DESIGN

5.1 Household Behavior

"Architecture is a machine for living in"[3], says Le Corbusier, one of the founders of modern architecture. This sentence shows that his architectural thinking at that time emphasized the functional purpose of buildings as artifacts built for human use. Although this idea tended to be too mechanistic that ignored many of the other factors involved in building. However, it is undeniable that the functions as the basic requirements that buildings should meet is the basic consideration of architecture design and construction, especially for residential buildings. Unlike other types of buildings, residential buildings are the most closely related to their users, the behavior needs of households affect the design of residential buildings in many ways, and residential buildings also determine the behavior and experience of users living inside in a certain way.

5.1.1 Behavior Need

Applying the well-known theory of Maslow's Hierarchy of Needs to the residential building area, the needs of the households can be divided into the following three levels: meeting the basic functions of daily life; pursuing the high quality at the physical and

[3] Le Corbusier. Towards A New Architecture [M]. Nanjing: Jiangsu Science and Technology Press, 2014

psychological levels; and realizing the self-worth of the households.[4] Among them, the last level is beyond the scope of this research because its subjective differences, which are too obvious. And the following will focus on the first two levels. The function purpose of residential building is affected by many factors, including geographical, environmental, cultural, technological ones and so on. With the fast development, the specifications of residential building design in China are improving as well. At present, the more widely accepted behavior needs of residential building include, but are not limited to rest and sleeping, entertaining, dining, excretion, cooking, bathing, washing, drying, storage, reading. Residential buildings not only need to meet these behavioral functions, but also need to meet the psychological and physical needs of users, including natural lighting and ventilation, thermal comfort, sight and visual need, privacy and so on. This chapter will focus on the natural lighting of residential buildings, household behaviors and their impacts on carbon emissions.

5.1.2 Household Behavior and Carbon Emission

The previous chapters define and discuss the main influencing factors of residential carbon emissions in this research, which can be classified as the materialization and the demolishment phase and the use phase. Among them, the carbon emission of the use phase is not only related to the energy consumption of the equipment which is determined by the physical performance of the residential enclosure structures, but also closely

[4] Abraham Maslow. Motivation and Personality [M]. Beijing: Renmin University of China Press, 2007

related to the behavior of household, like habits of using household appliance and other equipment. The impact of household behavior on residential carbon emissions is often studied isolated or ignored, systematic, comprehensive demonstration and research need to be further explored. With the research perspectives being continuous widening in recent decades, more and more scholars continue to raise awareness of energy conservation and carbon emission reduction in many areas. With sociology, behavior, environmental psychology and other multidisciplinary fields and other more perspectives emerging, the majority of scholars are gradually study in this area deeper. Household behavior has a potential impact on residential carbon emissions in residential buildings, which makes it worth to be explored.

5.2 Household Behavior Questionnaire

The above section outlines the impact of household behavior on residential carbon emissions. In order to explore further, a questionnaire survey is conducted, as a supplementary study for simulation, to try to understand how residential lighting, household behavior and emission reduction affect each other in hot summer and cold winter area. The entire research system is enriched by analyzing and summarizing the survey results, screening out the key factors.

5.2.1 Questionnaire Contents and Distribution

The questionnaire includes following aspects. Basic information of respondents, energy consumption behavior of household appliances, lighting evaluation and suggestions of improvement for their residential buildings.

The questionnaires were mainly distributed online, supplemented by field trips. Through the combination of the two methods, the scope of the sample basically covered most provinces and regions in hot summer and cold winter area in China, as well as different ages and classes. In this way, the questionnaire samples have a certain breadth, and can provide reference value to some extent.

5.2.2 Statistics and Analysis

292 questionnaires were handed out and 209 valid questionnaires were successfully collected, summarized and analyzed, representing 209 different individuals. According to other research findings, the basic information such as numbers and composition of family members, household income, characteristics of building such as shading type and other variables all may have an impact on the household behavior of using heating and cooling equipment. And the energy consumption of heating and cooling equipment has a direct impact on carbon emissions in use phase. Thus, the survey respondents focused on these aspects of statistics and analysis.

The main sample sources are Jiangxi Province (28.23%), Shanghai (21.05%) and Guangdong Province and northern Guangxi Province (13.4%) (Figure 5.1). And Figure

5.2 shows the subjective description of the residents living in different regions in the hot-summer and cold-winter area. It can be seen that hot, wet in summer and cold, wet in winter are the major climatic features in most areas, including the Yangtze River Delta and the middle and lower parts of the field along the Yangtze River, not the cold, dry climate like most north part of China.

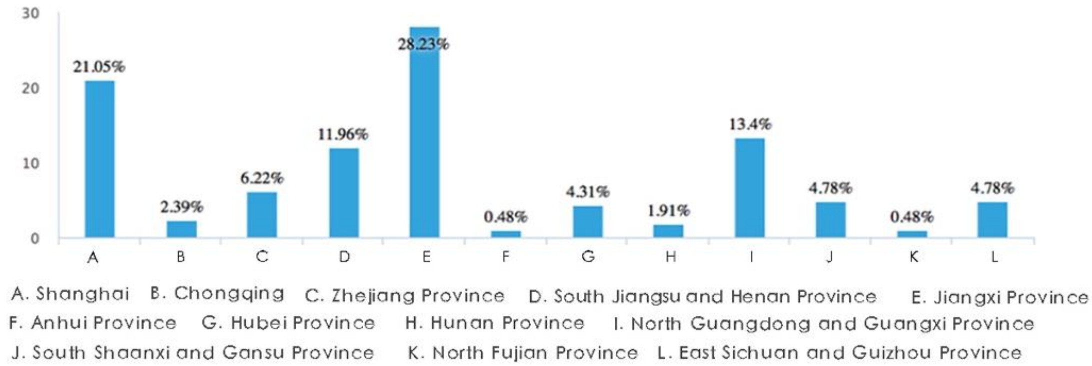


Figure 5.1 Geographical distribution

Source: Author

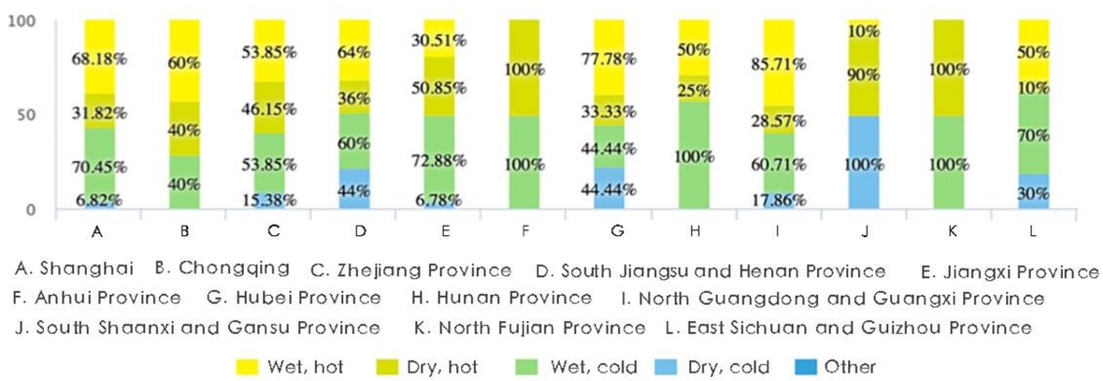


Figure 5.2 Climate subjective evaluation

Source: Author

A series analysis of the independent variables and dependent variables are conducted to explore which factors would affect the household behavior.

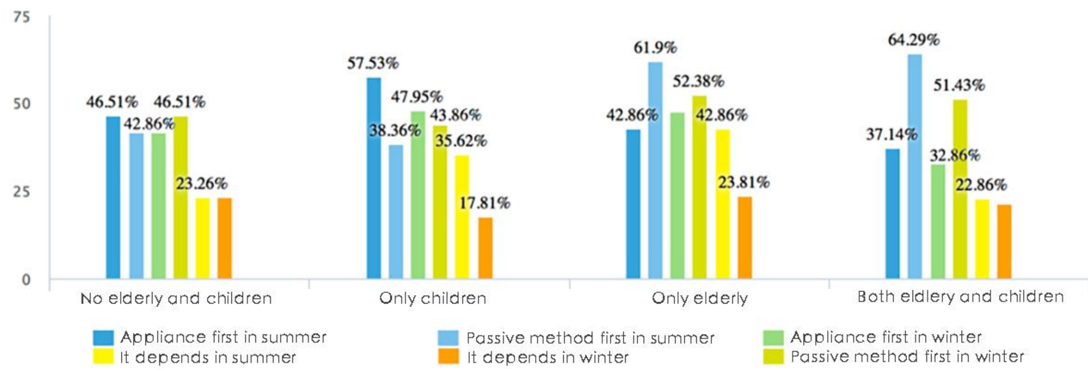


Figure 5.3 Household composition and cooling, heating preference

Source: Author

Based on Figure 5.3, there are two types of respondents who have the priority of using the natural way to regulate the indoor climate than the two types of respondents who do not have the elderly in the family composition. It confirms the thinking that older people tend to have a strong sense of energy saving, especially noticeable in summer. The data shows that the proportion of the former is 61.9% and 64.29% respectively, which is much higher than the 41.86% and 38.36% of the same category in the latter. At the same time, it also means that the former uses less air conditioning and heating equipment than the latter.

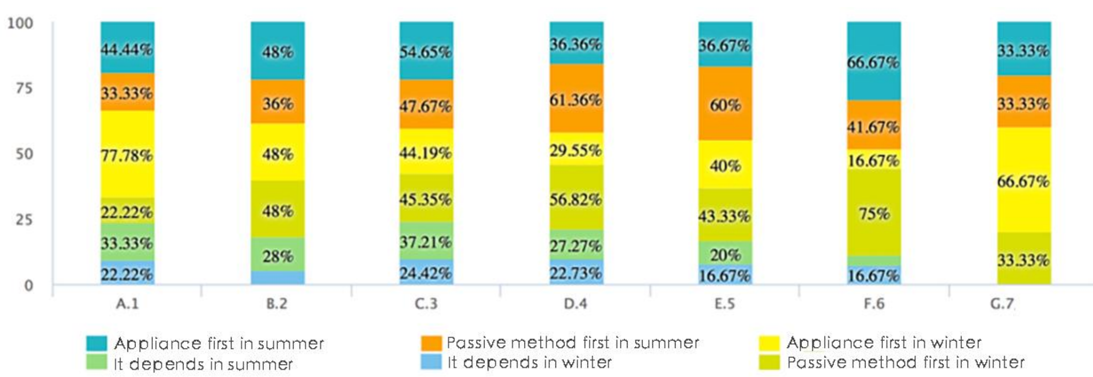


Figure 5.4 Number of family member and cooling, heating preference

Source: Author

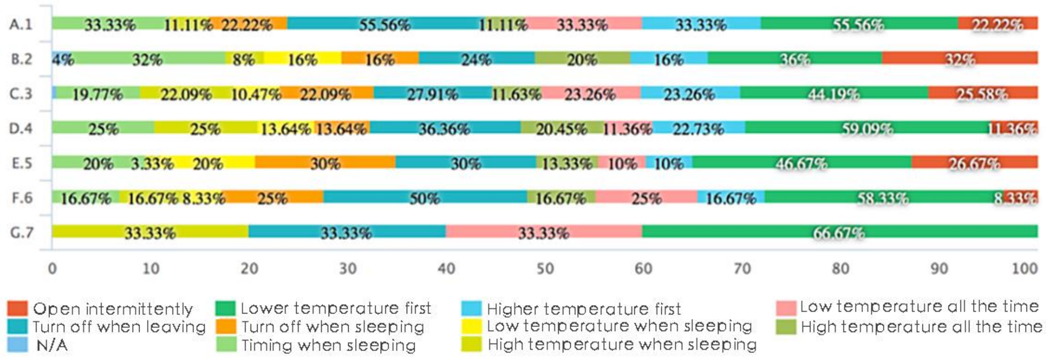


Figure 5.5 Number of family member and behavior of cooling equipment

Source: Author

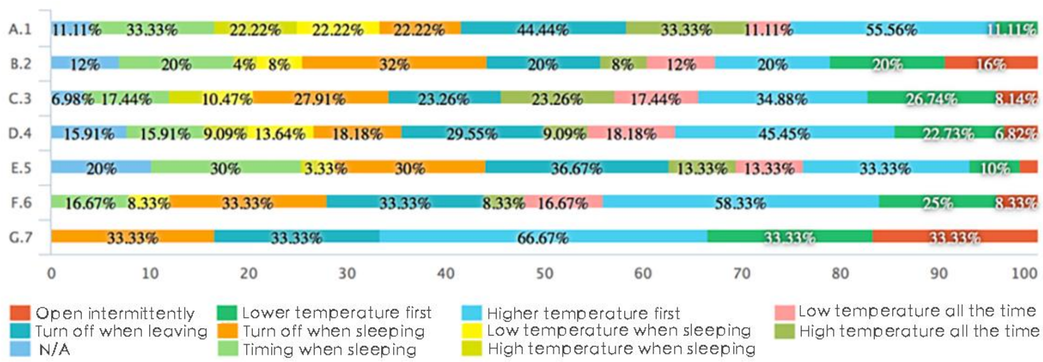


Figure 5.6 Number of family member and behavior of heating equipment

Source: Author

As Figure 5.4 to Figure 5.6 showing, the following inferences can be drawn. Medium size households (3-5) are more likely to use passive way of cooling and heating while those living alone and those big family with more than 7 members tend to use air conditioners in summer and heating appliances in winter; a wide acceptable behavior for using cooling and heating appliances is setting lower temperature at the beginning when using in the summer as well as setting higher temperature in the winter for a while before adjusting to comfort temperature; big family (more than 7) has a higher dependence for cooling in the summer than heating in the winter.

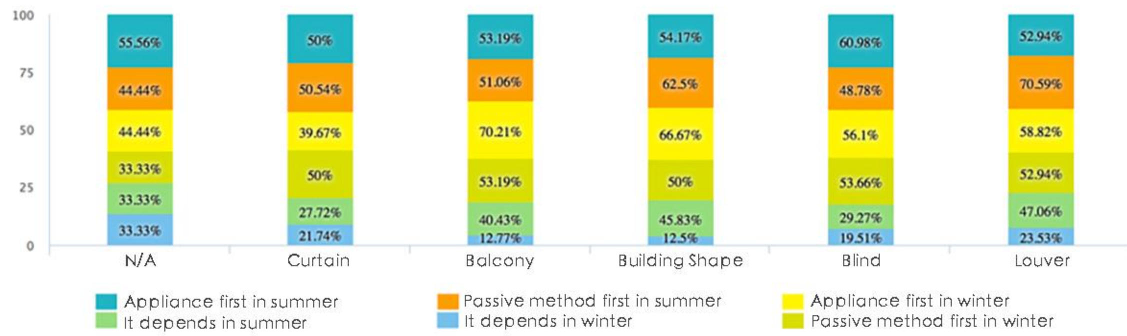


Figure 5.7 Shading and cooling, heating preference

Source: Author

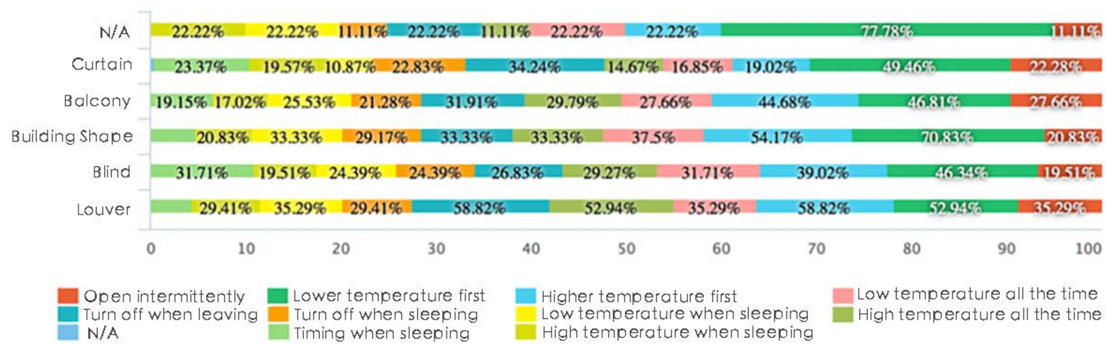


Figure 5.8 Shading and behavior of cooling equipment

Source: Author

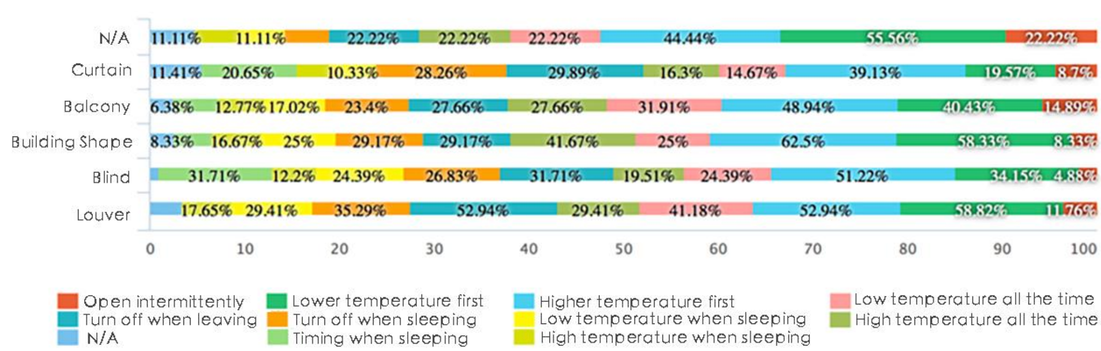


Figure 5.9 Shading and behavior of heating equipment

Source: Author

In addition to the behavior habits of different households, the factors of residential design will also have a certain impact on the use of equipment. The shading, for instance, is a common method for controlling direct sunlight and radiant heat into the interior in summer times, the effect of the physical characteristics of residential buildings is without doubt. As can be seen from chart 5.7 to chart 5.9, the potential behavior impact on household has been illustrated. In units with shading, the family members have a higher preference for passive cooling ways to enjoy a comfortable natural climate than the members living in the houses without any shading equipment. Equipped with the exterior louvers, household behavior of air conditioning in the summer has been shown an increment proportion to open intermittently than the counterparts of the units without shading (11.11%); while the proportion of household to set a low running temperature of cooling equipment decrease significantly as well; at the same time, the proportion of household to set high temperature of air conditioning in summer is relatively high in shading residential, especially for exterior shading louvers (35.29%). On one hand, among all forms of shading types shown in the figure above, the exterior shading types such as louvers, balcony and building shape shading have more influence in changing the behavior of setting the operating temperature of cooling equipment in summer than the interior shading form. On the other hand, conversely, when heating equipment was used in winter, the proportion of household to set operating temperatures in residential units without shading show a higher number in operating their devices intermittently (22.22%) than the counterpart of the residential units with shading.

Based on the form of questionnaire survey, this chapter mainly discusses a series statistical analysis on the samples about their residential units and equipment usage behaviors. It is clear that residential energy consumption and carbon emissions are not only determined by the physical characteristics of the residential buildings under the ideal simulation circumstance in the previous chapter of this research, household behavior is also an important factor, which can be largely affected by the residential design.

CHAPTER 6 SUMMARY AND DISCUSSION

The research work of this paper is conducted by applying simulation, empirical study, field investigation and research and so on. Through the quantitative analysis, the possibility of carbon emission reduction in residential lighting design is discussed in a certain framework. The main conclusions are summarized as follows.

(1) Height of windowsill. Based on the simulation and empirical research, when the window area is a fixed value, the most cost-effective approach to improve the indoor lighting coefficient is to increase the height of the windowsill appropriately, and the effect gets to the best when height of the windowsill reaches about 0.90m; after this turning point, the lighting coefficient goes down with height of the windowsill increasing; the evenness of indoor natural lighting distribution improved with the height of the windowsill increasing; as for the carbon emission consideration, with the increment of indoor lighting coefficient, the carbon emission increment is so small that can be ignored. Combining these two aspects, design an appropriate windowsill height can be an efficient way in residential design for improving indoor lighting conditions to some extent without causing significant carbon emission increment, which is a suitable sustainable design strategy under the context of carbon emission reduction. And the recommendation height for windowsill is 0.90m.

(2) Window/wall ratio. By adjusting the window/wall ratio of different orientations, or in other words, changing the window area in each direction respectively when the total area of each direction is a fixed value, the residential lighting efficient will be significantly affected. Increasing the window/wall ratio is a direct way to improve the residential lighting condition, but it is also accompanied by a considerable increment in carbon emissions in both use, materialization and demolition phase. And the growth rate between the carbon emission increment and lighting coefficient shows a linear correlation; taking the direction of the window into consideration, the order of carbon emission increment per unit is south > east ≈ west > north; the order of indoor average lighting coefficient increment is east ≈ west > north > south. The recommendation window/wall ratio for south direction can be summarized as 0.40-0.50.

(3) The shape of window. When the window/wall ratio is a fixed value, or in other words, the total area of window is a fixed value, the carbon emission increment caused by changing the shape of window in each direction is almost negligible. However, the shape of window does make a notable difference when it comes to the indoor lighting coefficient distribution. When window/wall ratio is less than 0.3, increasing the window width has significant advantages for increasing the lighting coefficient compared with increasing the window height, the difference between these two is almost up to 7 times; while window/wall ratio is more than 0.3, the advantages of adjusting the window width in increasing the indoor natural daylighting effect still exist, but the differences between

these two gradually decrease. Given the carbon emission can be ignored for adjusting the shape of the window, which in most situations, widths and heights in residential buildings, if other design conditions permit, the better design strategy of improving lighting from the carbon emission perspective is to increase the window width first instead of increasing the window height. Especially when the window height or the height of windowsill is below 30% or less of the floor height.

In addition, through a series of qualitative analysis of questionnaire survey, it can be concluded that residential lighting design has the potential to reduce carbon emissions by influence the household behavior toward the operation of cooling and heating equipment, such as proper shading design will affect the cooling habits and reduce household reliance on cooling equipment so that it will reduce carbon emission in use phase to some extent.

In summary, a considerate and appropriate lighting design has many potentials in balancing carbon emissions and lighting conditions.

CHAPTER 7 CASE STUDIES

As the theoretical research outcomes have been thoroughly studied in the previous chapters, however, without solid proof of existing cases, these findings seem to be not so convincing and vivid. There is no doubt that many built buildings are designed with human intellectual inspirations to fully take advantage of natural lighting while not consuming much energy. On one hand, these projects provide a comfort lighting environment for the users that they can have a nice illuminated indoor space. On the other hand, they also convey a deep consideration of sustainable design that balance the relationship between quality and impact to the nature. Therefore, in this chapter, two projects, one in Shanghai and the other in the United States of America, are selected as references to be fully analyzed for applying strategies into practice, which in some extend, can provide some support and inspirations for the design proposal in the next chapter that guided by the research progress of this dissertation.

7.1 One Park Gubei, Shanghai

The One Park Gubei is one of the finest residential housing projects in Shanghai, China. It is located in Hongqiao District. The site area is $82000m^2$, total floor area is $143000m^2$, 315 households in total, each has a wide view to the surrounding environment. The site plan and the aerial view of the project is shown below (Figure 7.1 and 7.2).

Figure 7.1 Site plan of One Park Gubei, Shanghai

Source: One Park Gubei

Figure 7.2 Aerial view of One Park Gubei, Shanghai

Source: One Park Gubei

The reason why the One Park Gubei is chosed as an example for guiding the following design lies in the delicate design of the façade and the shear wall as can be seen clearly in the elevation, plan and façade details (Figure 7.3-7.5). Its window/wall ratio is around 0.5 for south and north direction, which ensures the wide view and ample natural lighting and 0.2 in west and east direction, which protects the indoor space from overexposure of the direct sunlight in early morning and dusk. And the shear wall is designed in particular shape so that it not only become the structure element, but also a shading device for the windows. Meanwhile, it helps to create the rhythm of the whole façade and keep the whole building in a simple but beautiful way.

Figure 7.3 Typical plan of One Park Gubei, Shanghai

Source: One Park Gubei

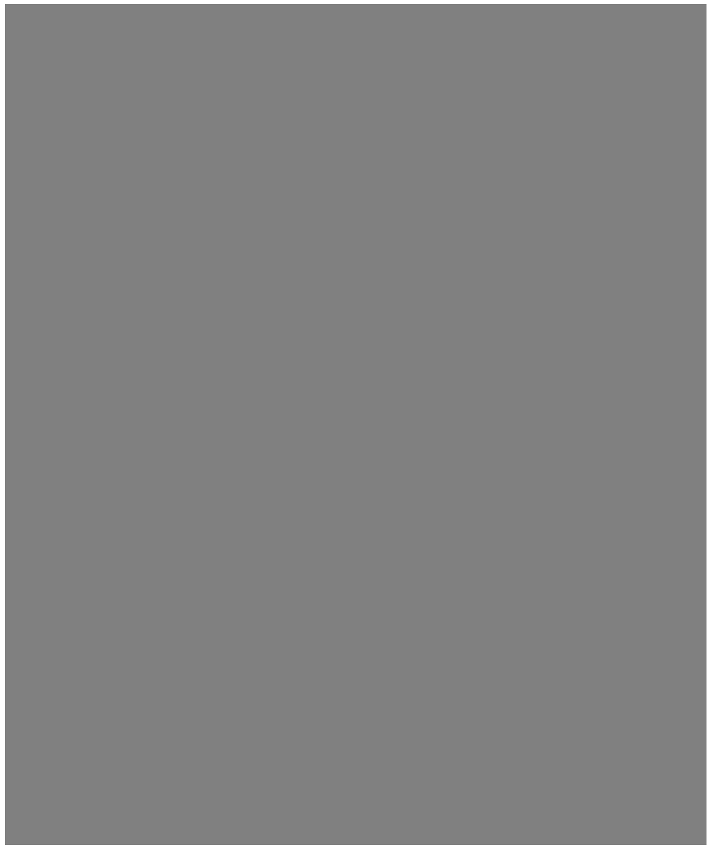


Figure 7.4 Typical elevation of One Park Gubei, Shanghai

Source: One Park Gubei

Figure 7.5 Typical façade detail of One Park Gubei, Shanghai

Source: One Park Gubei

7.2 Research Support Facility of the Department of Energy, Golden

The Research Support Facility (RSF) is a very significant building for the Department of Energy (DOE). The main reason why I choose this project as a good example, though it is not a residential project, it is a representative of high-performance buildings with aesthetical consideration through an integrated design. Not only is the RSF designed to meet the LEED Platinum rating as defined by the US Green Buildings Council, it is also to be the first Zero Energy Building (ZEB) of its kind.

Figure 7.6 Daylighting analysis of Research Support Facility of the Department of Energy

Source: RNL Design

The project utilizes strategies that leverage light and air to increase energy performance and improve workplace performance. Daylighting is the keystone strategy for the project because it significantly impacts energy consumption and productivity (Figure 7.6). The building massing and window design optimize control and harvesting of daylight. Virtually every workspace in the main office wings is covered with daylight. Overall, 92% of all regularly occupied spaces are daylight (Figure 7.7).

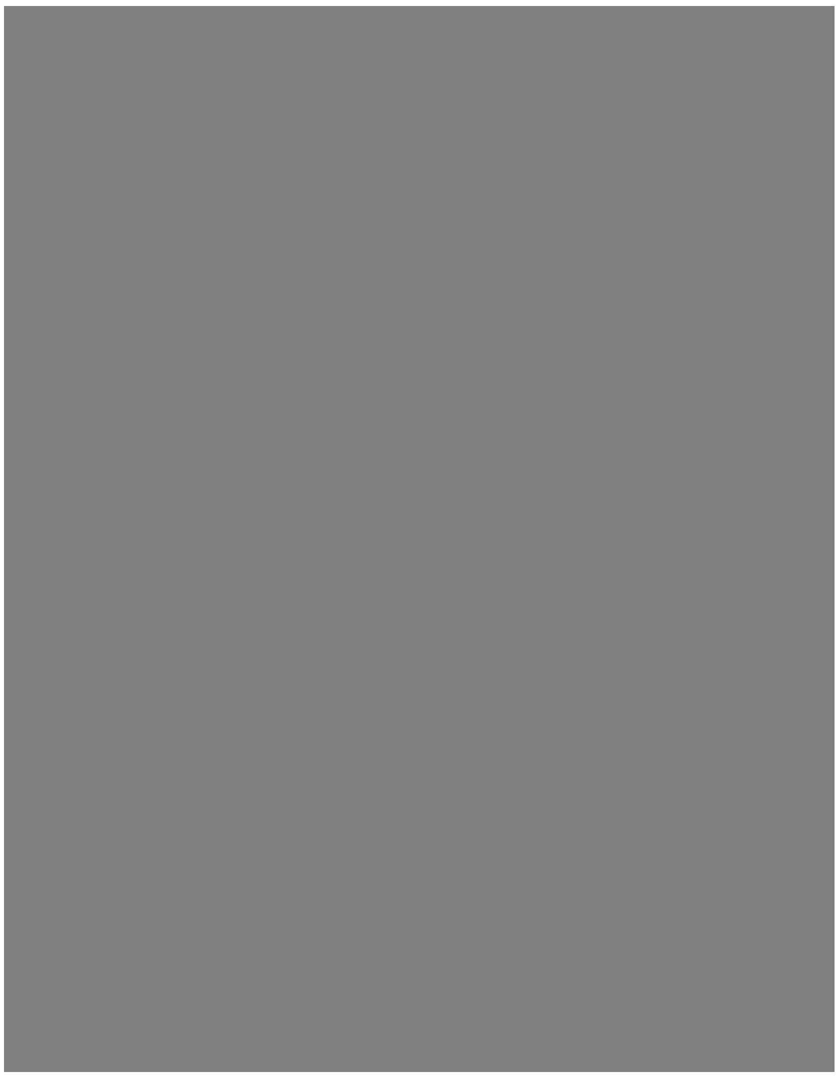


Figure 7.7 Interior view of Research Support Facility of the Department of Energy

Source: AIA

Figure 7.8 South window analysis of Research Support Facility of the Department of Energy

Source: RNL Design

This project is a showcase of sustainable high-performance design. It demonstrates the integration of high performance design features and practices with energy efficient technologies to provide a comfort indoor space for users.

As illustrated clearly in the diagram shown above (Figure 7.8), a special window type with lighting shading shelf is designed for the south façade. On one hand, the shading shelf can prevent the indoor space from over exposure of sunlight, on the other hand, it reflects the lighting to illuminate the upper indoor space with the help with specific light louver. And the whole south façade is covered with these elements and they become the characteristics of this building (Figure 7.9).

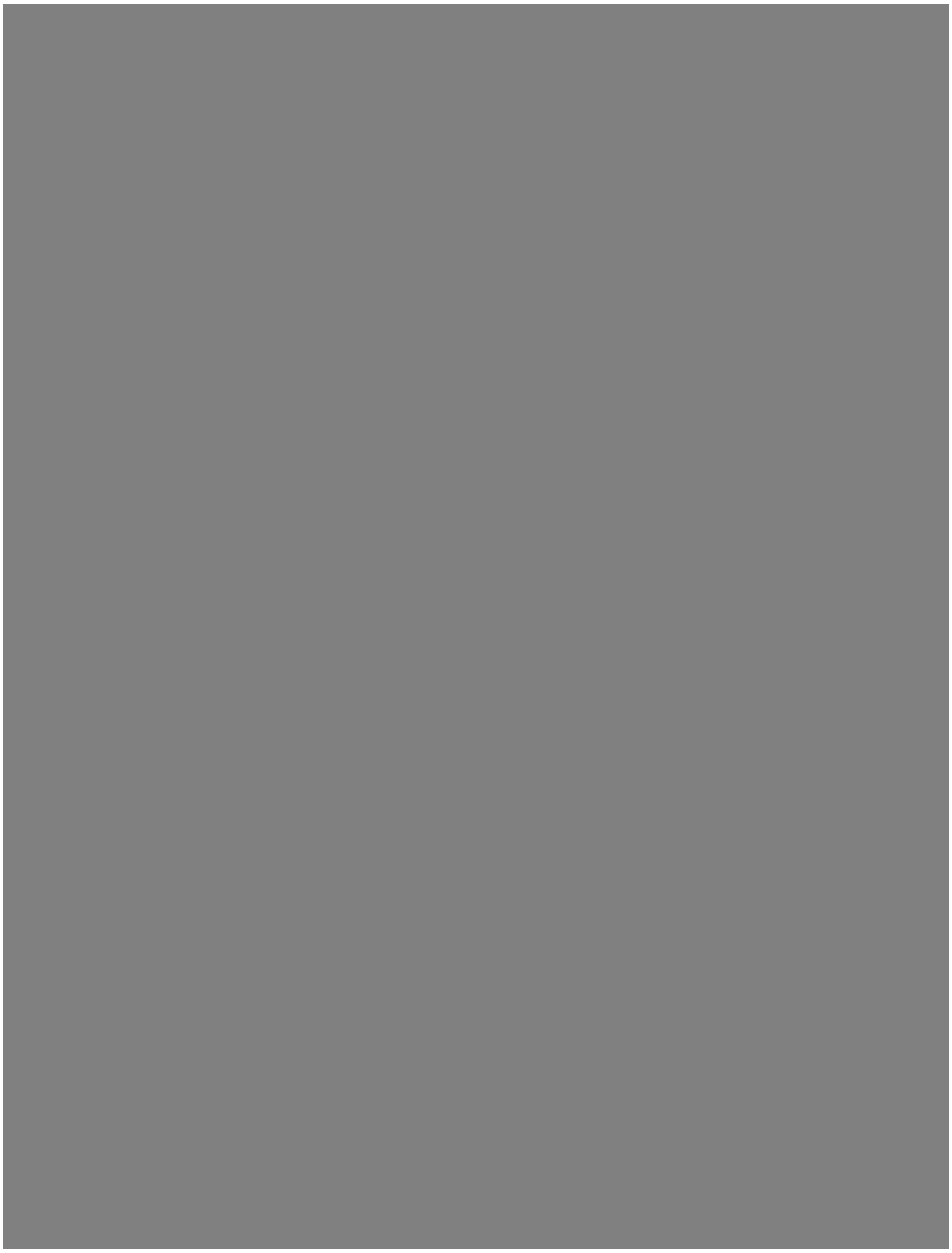


Figure 7.9 South façade of Research Support Facility of the Department of Energy

Source: RNL Design

CHAPTER 8 DESIGN OF CITY HYATT, SHANGHAI

8.1 Project Information

The project of City Hyatt is located in Putuo District, Shanghai, China. The north side of the site is facing Suzhou River and Mengqing park which is an urban greenery space. It has a great view and landscape advantage towards the riverside. The original design was positioned as a middle class residential project, completed in 2010. This design will be based on the No.6 building in this residential project which is located on the north side as a design reference. The original building is a 12-storey residential building with a staircase and an elevator, the building area of the standard apartment is about 140m^2, while the 11 and 12 floor is designed as a penthouse. It applied a shear wall structure system and the entrance was assigned in the north part of the first floor which was open to the surrounding landscapes.

This design project will be a proposed design option according to the research outcomes which have been discussed thoroughly in the previous chapters. Multiple integrated guidelines will be applied in this specific design to improve the lighting condition and try to achieve a better balance among living quality, energy consumption and carbon emission for the existing project.

Figure 8.1 South aerial view of the existing residential buildings for the project

Source: TJAD

8.2 Design Research

The following analysis are based on the continued part of the previous questionnaire survey. It aims to give some initial understanding of the lighting condition for urban residential housing projects in hot-summer and cold-winter zone. According to the survey results, several design aspects and potential of lighting can be clearly addressed.

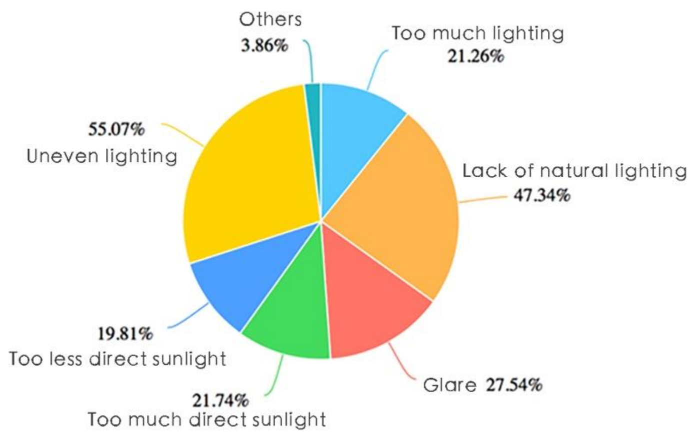


Figure 8.2 Evaluation for residential natural lighting aspects

Source: Author

Figure 8.2 shows the comprehensive evaluation of residential lighting aspects from sample households and also shows its dissatisfaction with many residential lighting aspects, such as the uneven lighting (55.07%) and the lack of natural lighting (47.43%); and followed by the glare (27.54%), with direct sunlight issues also included.

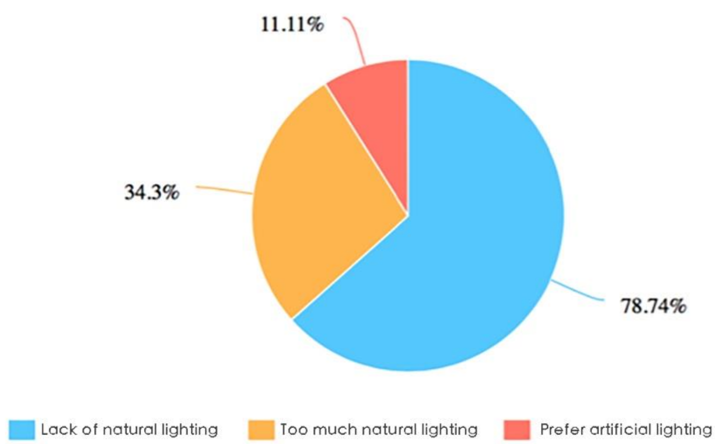


Figure 8.3 Overall evaluation for residential natural lighting condition

Source: Author

As the overall evaluation for residential natural lighting condition shows (Figure 8.3), only 11.1% of the samples (23) have a preference for artificial lighting instead of natural lighting; and the biggest problem nowadays is the lack of natural lighting.

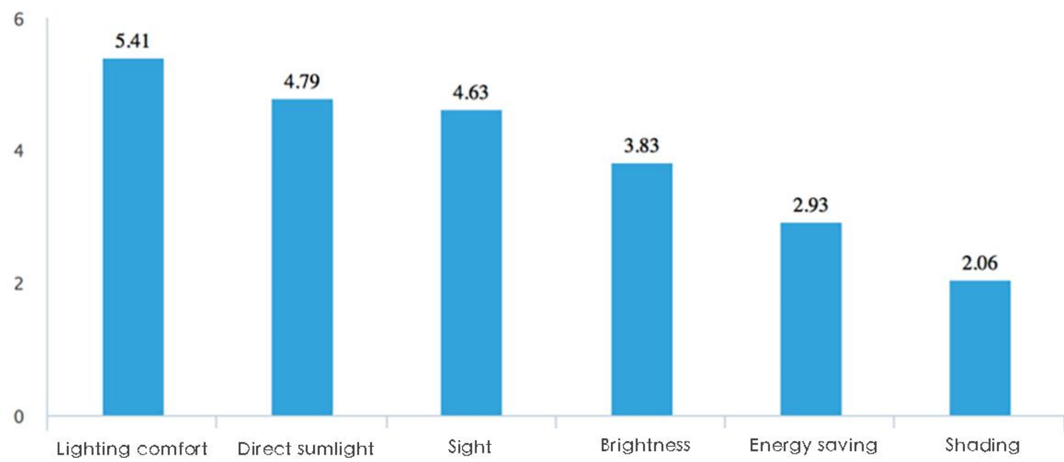


Figure 8.4 Importance ranking for residential natural lighting aspects

Source: Author

Figure 8.4 gives a ranking for what is thought to be important in residential lighting. The higher the value is, the more important it is, vice versa. Therefore, the order of importance for residential lighting based on this survey is as follows: lighting comfort > direct sunlight > sight > brightness > energy saving > shading.

8.3 Design Goal

As summarized in the analysis statements listed above, the target of this design is to better the lighting condition, especially in kitchen, toilet and bedroom (Figure 8.5), including enhancing natural lighting without comfortable glare and improving the lighting distribution to make it more even; also, taking energy consumption and carbon emission into consideration to make a balanced design.

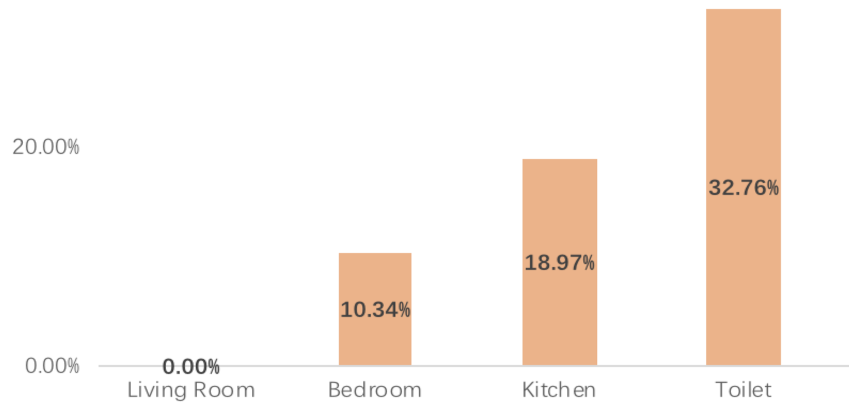


Figure 8.5 Rooms with least satisfaction

Source: Author

8.4 Design Drawings

These segment is a collection of drawings showing the proposed design. (Figure 8.7-Figure 8.24).

The proposed design will be based on the specific building as shown in the site plan (Figure 8.7), highlighted in red, the building is the major and representative type in this residential district. The proposed design will try to minimize the design changes of the indexes that are irrelevant to lighting design in order to keep the design consistent with the theoretical research.

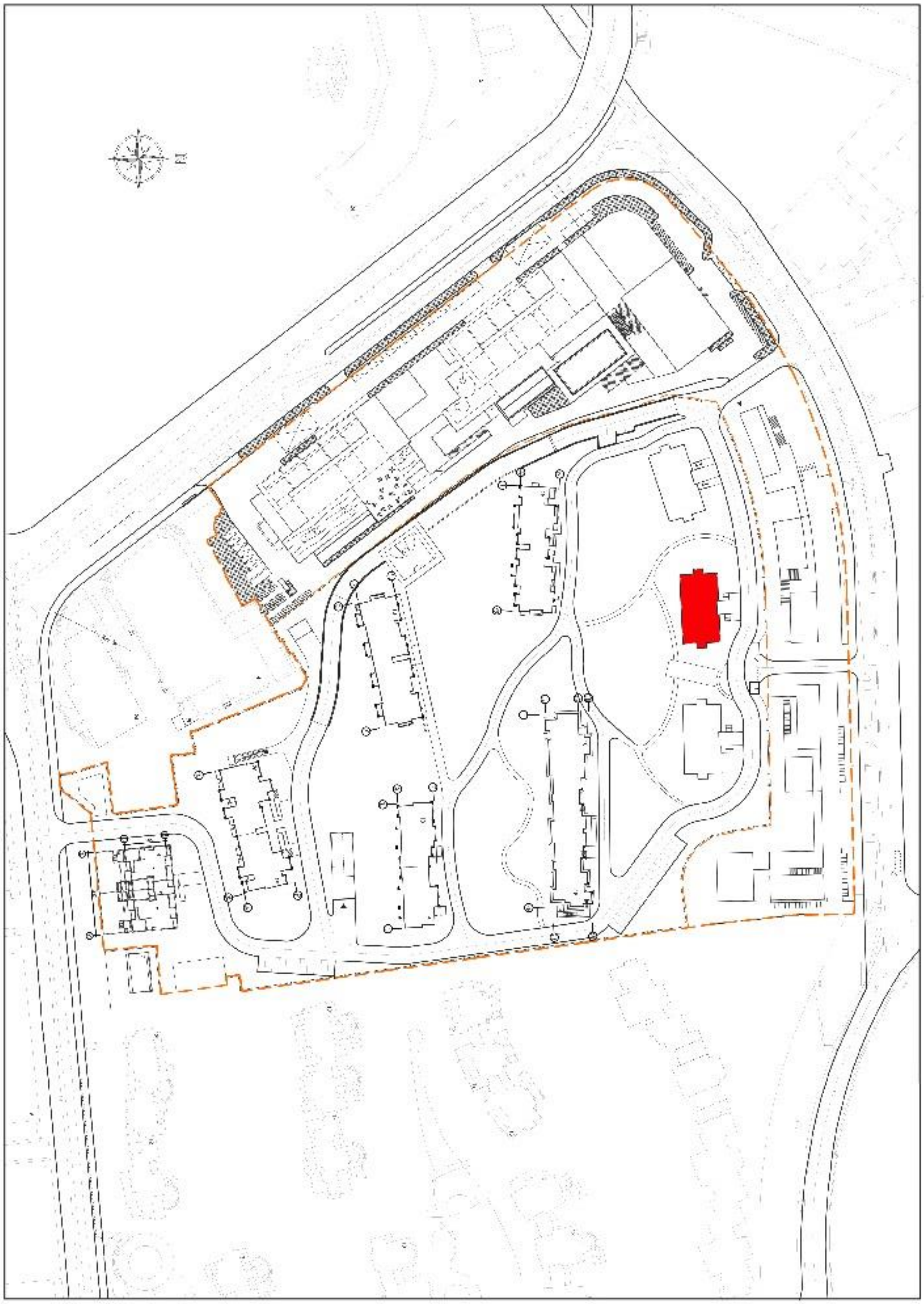


Figure 8.7 Site plan

Source: TJAD

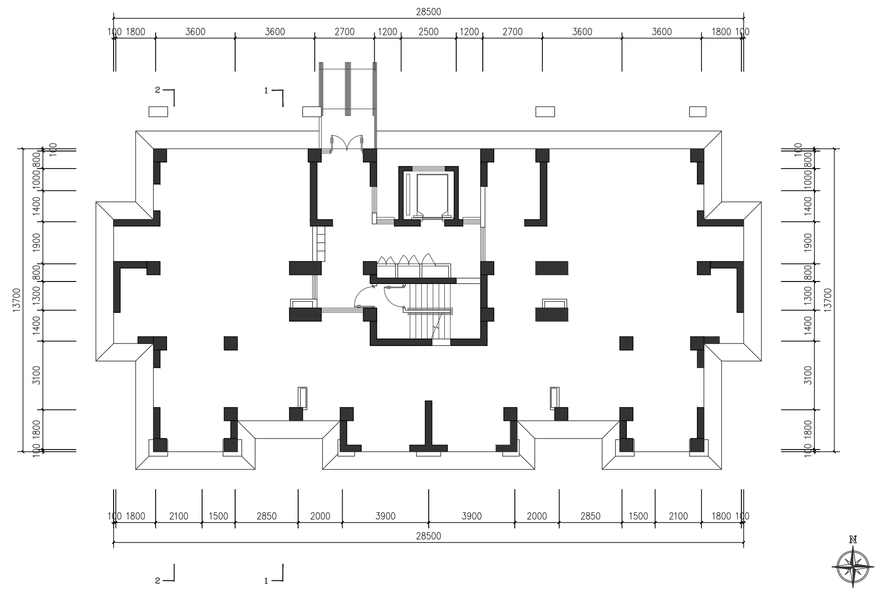


Figure 8.8 1F floor plan (existing)

Source: TJAD

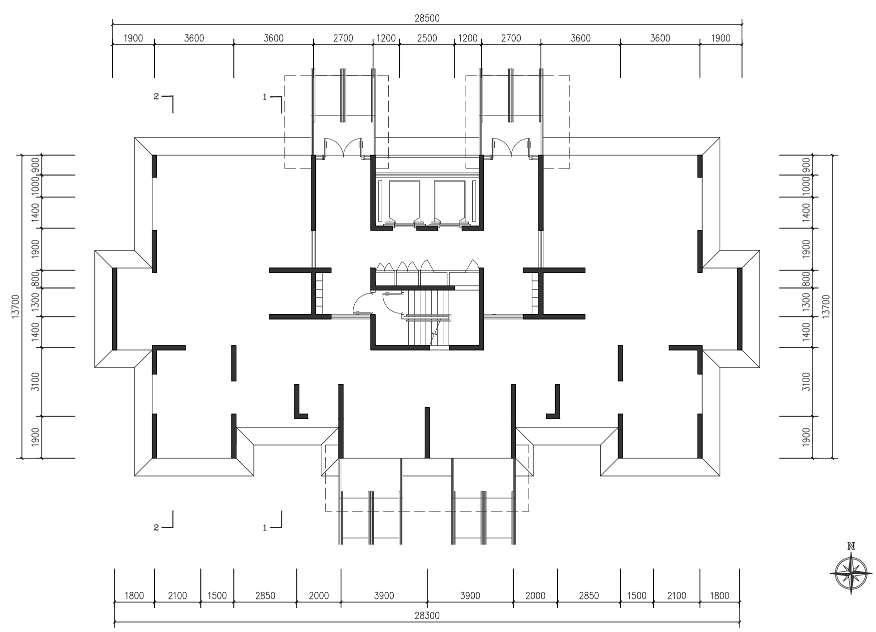


Figure 8.9 1F floor plan (proposed)

Source: Author

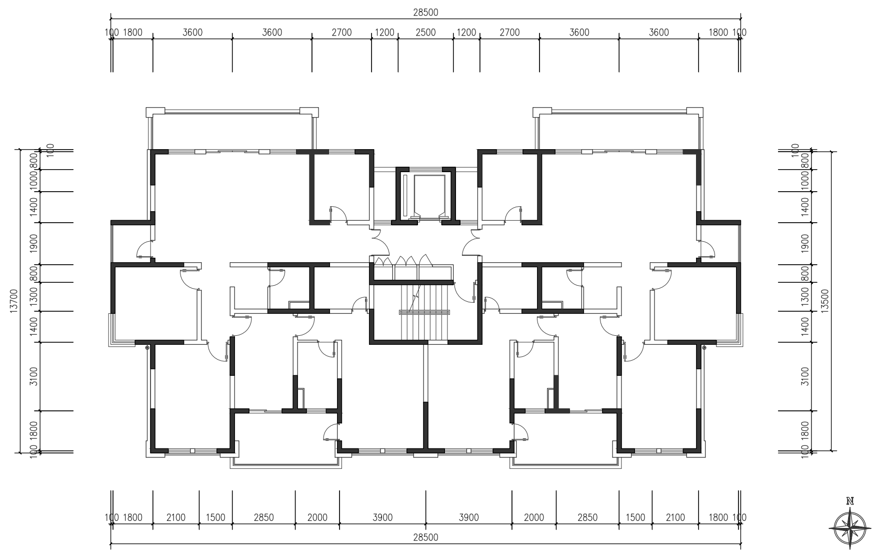


Figure 8.10 2F-10F floor plan (existing)

Source: TJAD

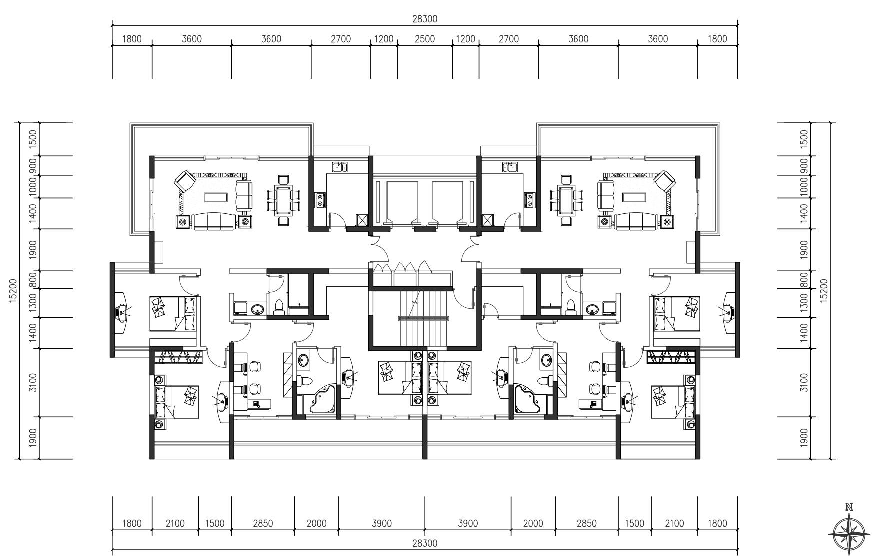


Figure 8.11 2F-10F floor plan (proposed)

Source: Author

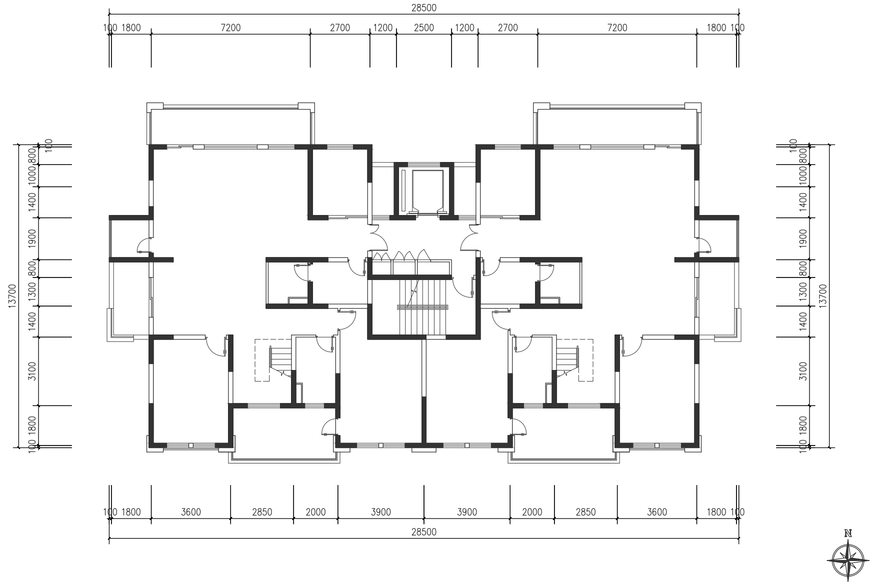


Figure 8.12 11F floor plan (existing)

Source: TJAD

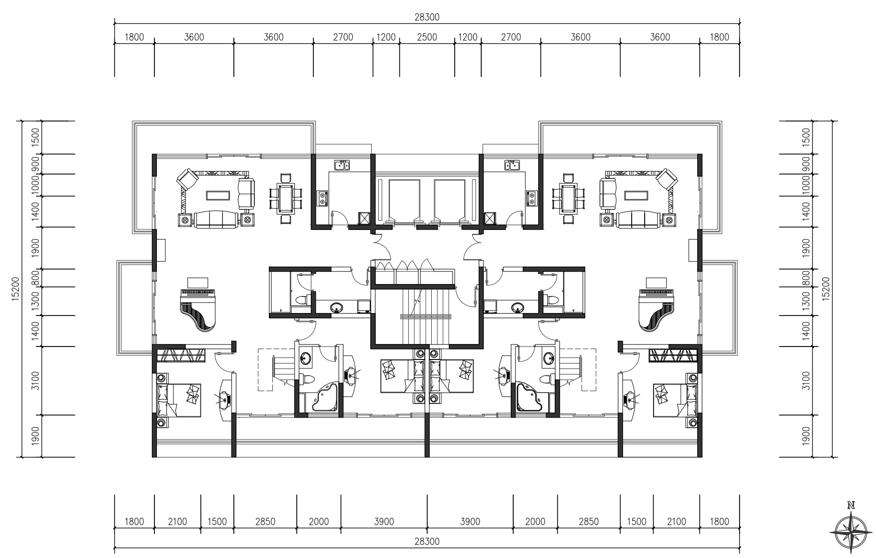


Figure 8.13 11F floor plan (proposed)

Source: Author

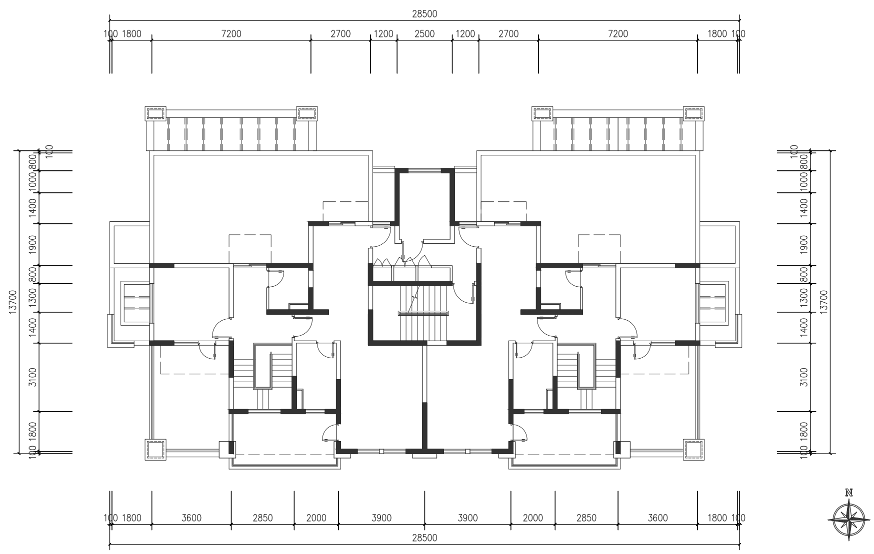


Figure 8.14 12F floor plan (existing)

Source: TJAD

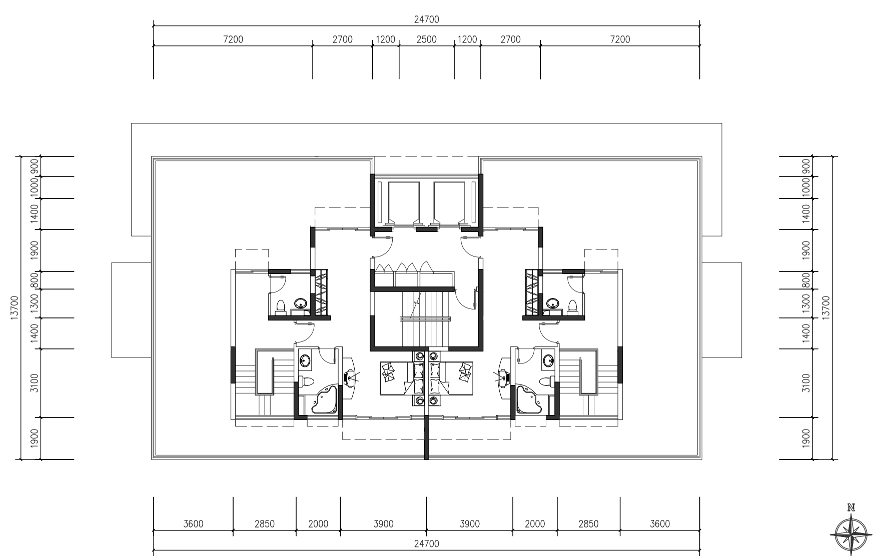


Figure 8.15 12F floor plan (proposed)

Source: Author

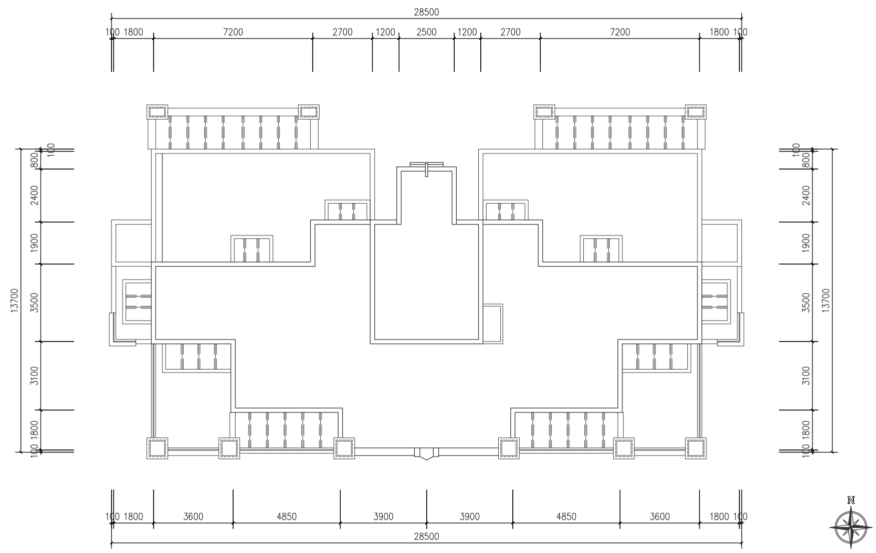


Figure 8.16 roof plan (existing)

Source: TJAD

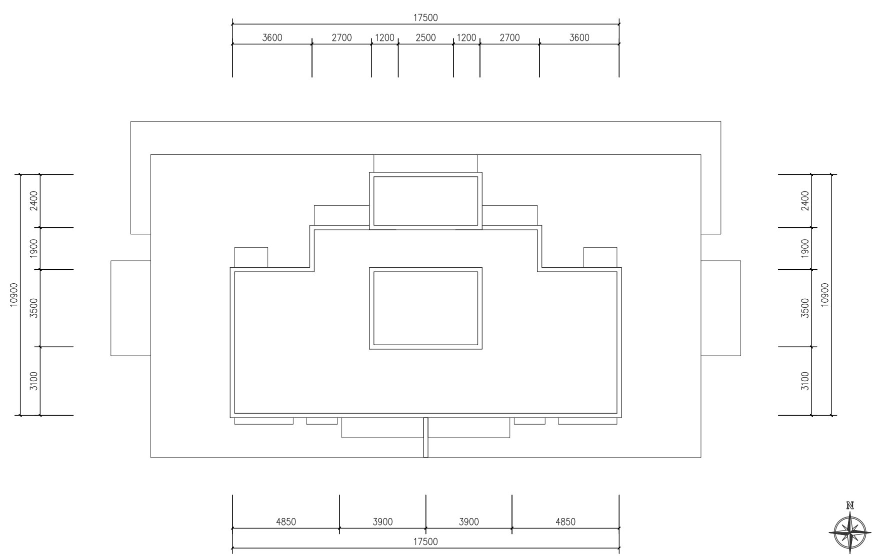


Figure 8.17 roof plan (proposed)

Source: Author

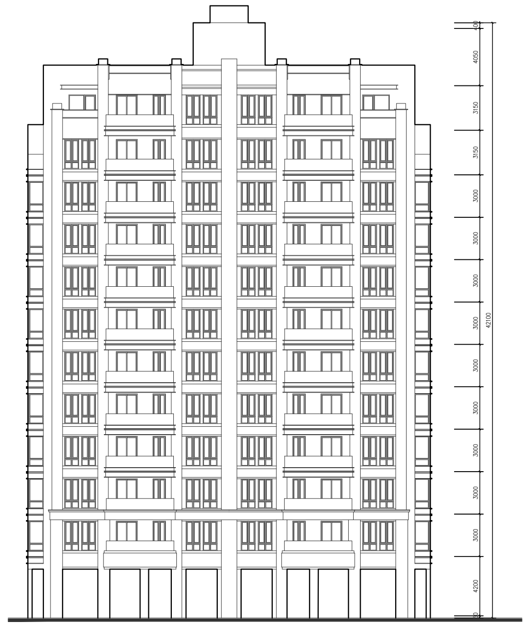


Figure 8.18 Elevation (existing)

Source: TJAD

Figure 8.19 Elevation (proposed)

Source: Author

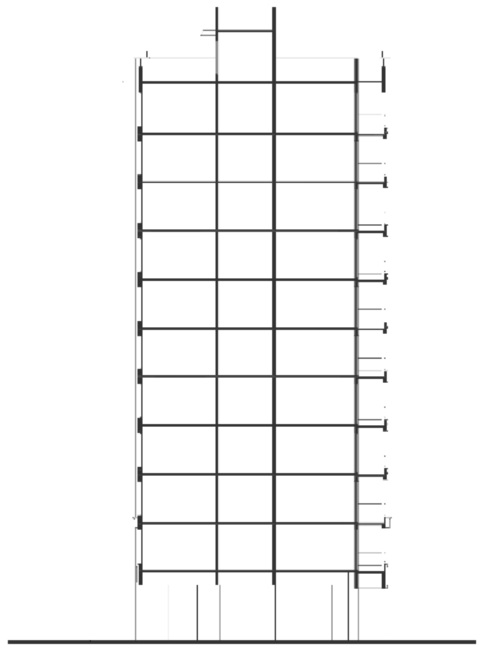


Figure 8.20 Transverse section (existing)

Source: TJAD

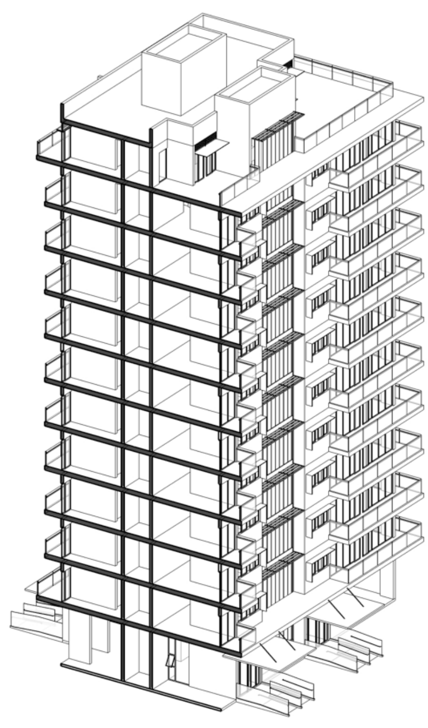


Figure 8.21 Transverse section axonometric (proposed)

Source: Author

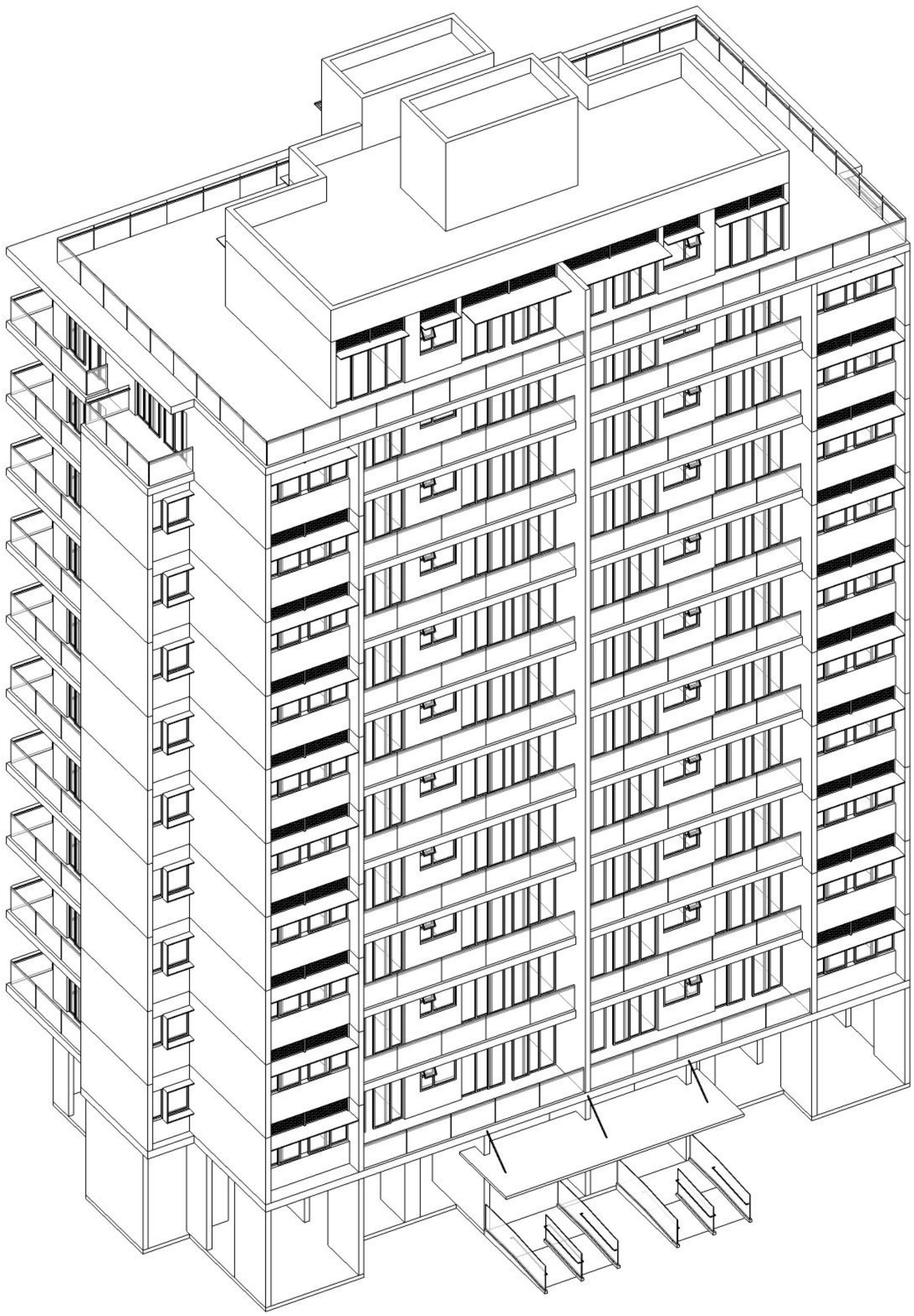


Figure 8.22 South axonometric (proposed)

Source: Author

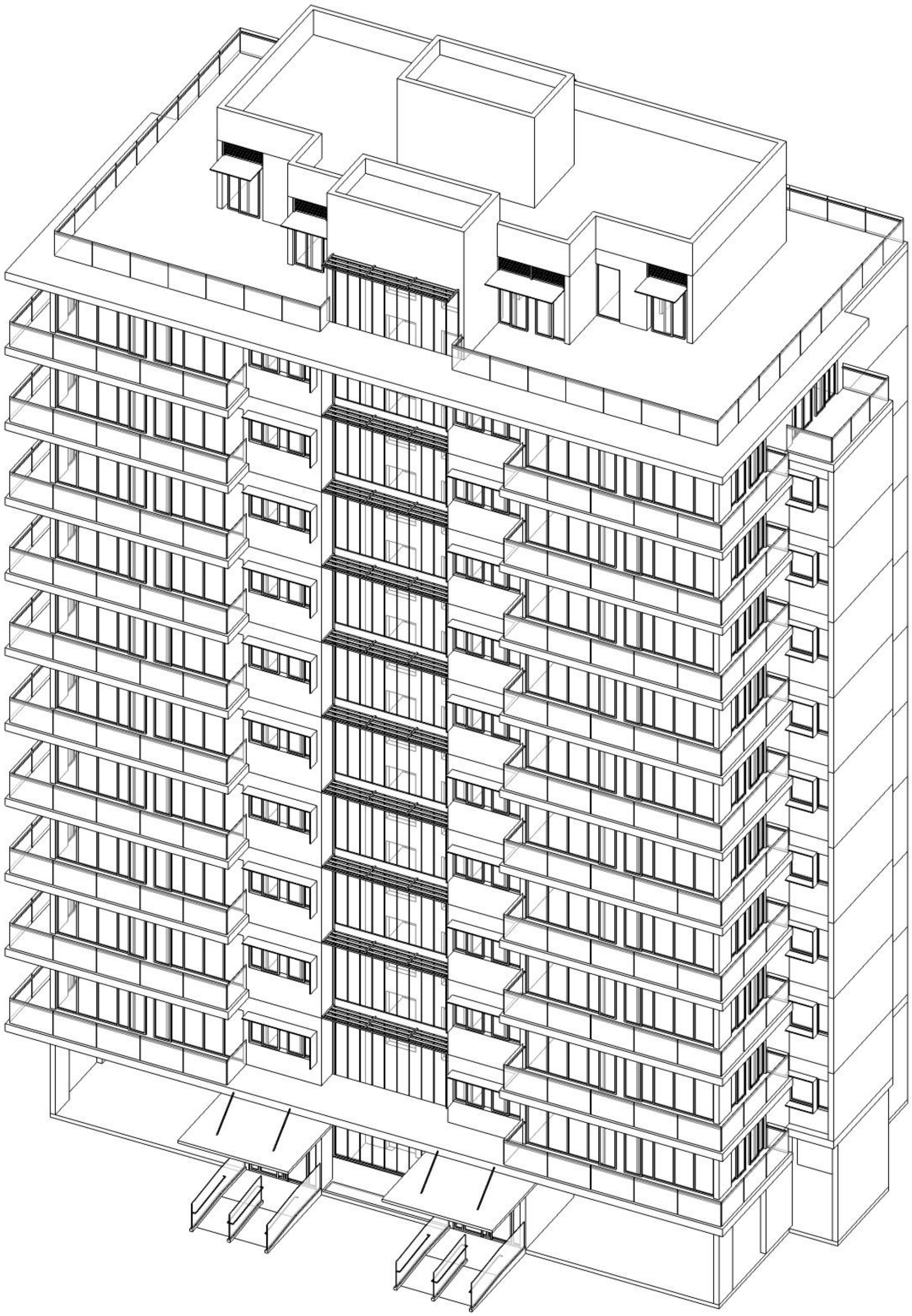


Figure 8.23 North axonometric (proposed)

Source: Author

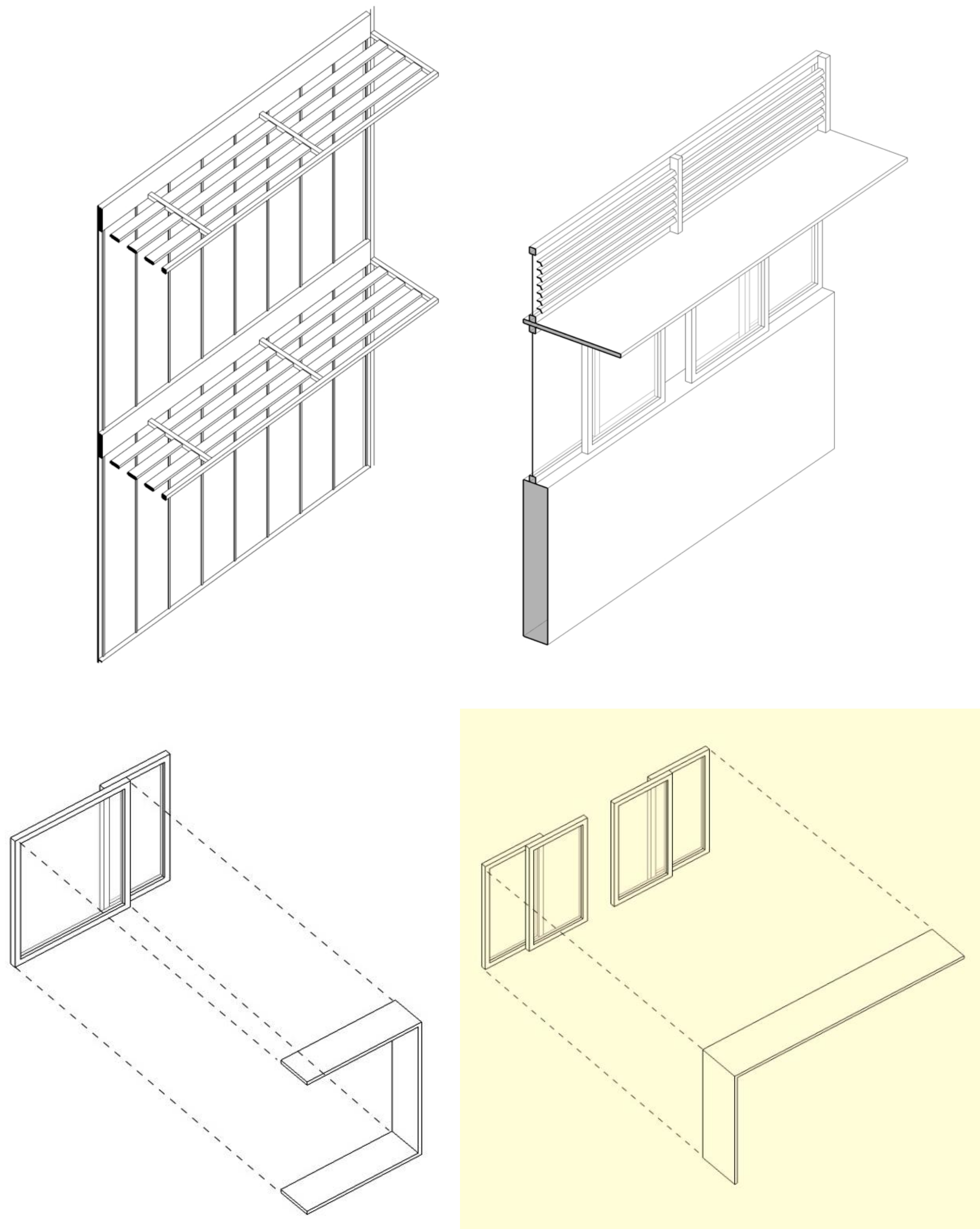


Figure 8.24 Façade detail (proposed)

Source: Author

8.5 Design Analysis

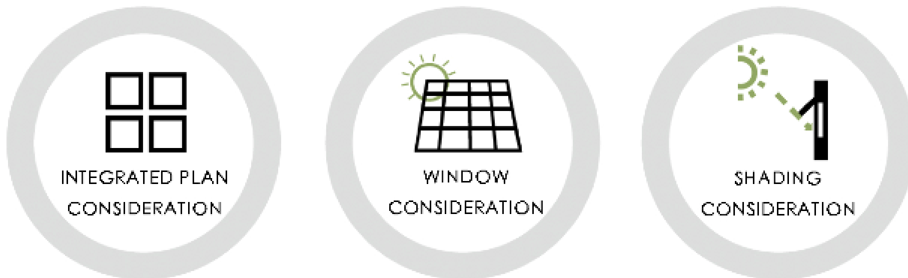


Figure 8.25 Design element concept

Source: Author

Comparing to the existing design, the original plan structure which includes transportation core in the middle and two household unit on the wing is kept. However, the length of each room facing south are modified in order to get more day lighting, the balconies are reshaped to direct and reflect more lighting in the winter while prevent overheat gain in the summer time. The same tricks happen in the study rooms and bedrooms. The shear wall system is redesigned to reduce the view block and make the whole living space more transparent and efficient.

As for the window part, window shapes are designed as horizontal, which is wider than the original design; the window sill height is arranged as 1.20m to reallocate the lighting distribution for the kitchen; the window/wall ratio is reduced on western and eastern side to prevent heat gain in the twilight and dawn, while the south and north window/wall ratio is increased not only to provide visual contact to the landscape, but also to gain more daylighting; the shading devices are designed by calculation, by putting these shading panels and balconies, the interior space can gain enough daylighting while not gain so much direct sun energy and overheating.

8.6 Comparison Analysis

In order to see how those design effort (Table 8.1) change the existing situation, here are some comparison studies of lighting condition simulation and carbon emission estimation according to the previous research.

Table 8.1 Basic information of the existing and proposed project

Orientation	South	
Building Shape Coefficient	0.39	0.35
Building Area	3442.17 m^2	3291.94 m^2
Window/Wall ratio	East 0.05； South 0.35； West 0.05； North 0.35	East 0.10； South 0.50； West 0.10； North 0.60
Windowsill Height	0.60 m	0.90 m
Wall Type	Concrete block, 2 coat stucco over porous surface, R5 XPS continuous insulation	
Window Type	Aluminum operable low-e double glazing	

Source: Author

The following figures and charts shows the lighting coefficient distribution simulation of the existing and proposed building. Through optimization of the existing design, indoor lighting condition is improved by a large margin (average improvement is 44%). In addition, not only the average lighting coefficient is higher than the existing building, as can be seen directly from figures shown below, the evenness of indoor lighting distribution is better as well.

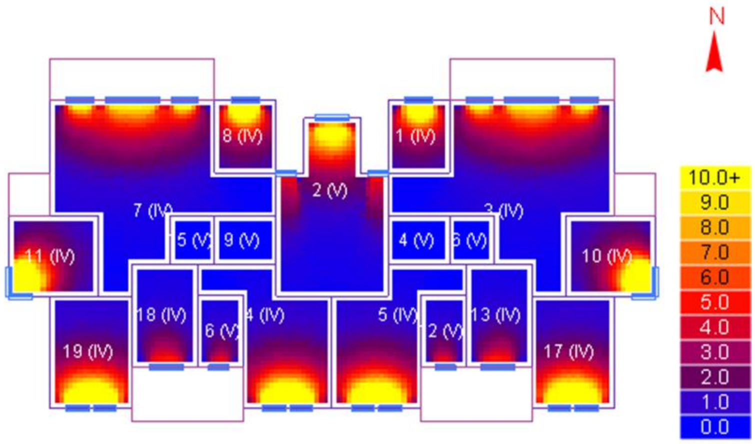


Figure 8.26 Lighting coefficient distribution simulation (existing)

Source: Author

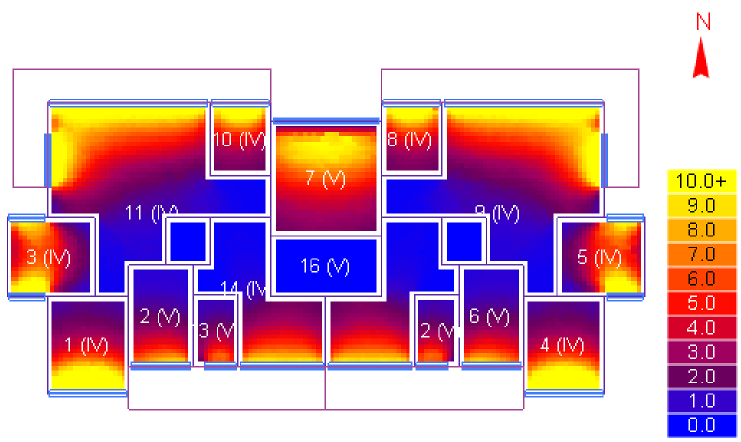


Figure 8.27 Lighting coefficient distribution simulation (proposed)

Source: Author

Table 8.3 Average lighting coefficient of projects（%）

Room	Living Room	Bedroom	Kitchen	Toilet	Average
Existing	1.90	4.30	4.60	1.40	3.05
Proposed	4.00	5.40	5.40	2.80	4.40

Source: Author

Table 8.4 Annual energy consumption simulation of Projects (KWh/m^2)

Category	Cooling	Heating	Total
Existing	21.65	36.23	57.89
Proposed	27.54	27.65	55.20

Source: Author

For the carbon emission part, according to the formulas for carbon emission calculation proposed in previous chapters, the carbon emissions of both buildings are listed in the following chart.

Table 8.5 Estimated carbon emission of projects (50 years) (tCO_2eq)

Category	Materialization and Demolition Phase	Use Phase	Total
Existing	762.74	7003.25	7765.99
Proposed	1073.77	6386.38	7460.15

Source: Author

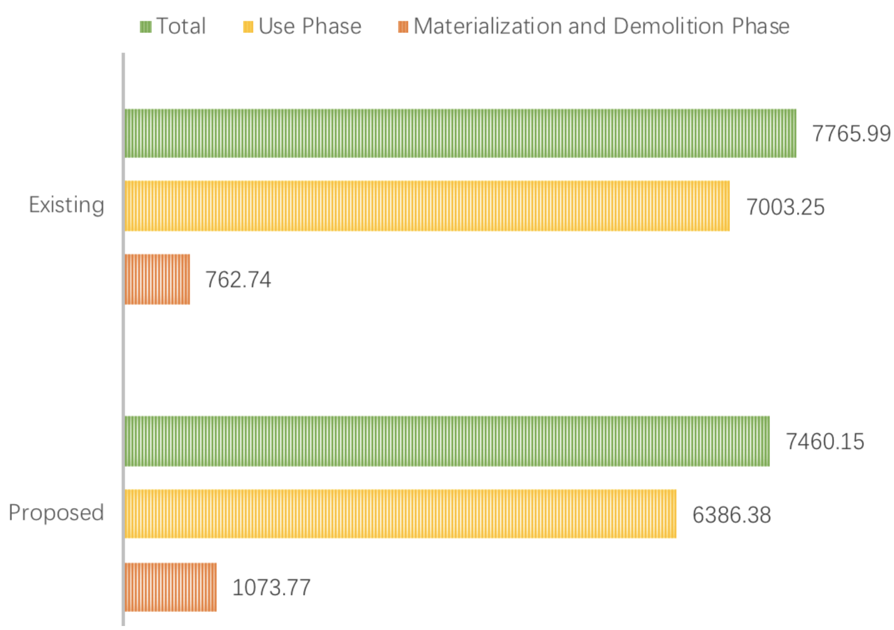


Figure 8.28 Estimated carbon emission comparison (50 years) (tCO_2eq)

Source: Author

From the charts and figures shown above, comparing to the existing building, the carbon emission, with the proposed design, reduced from the 7765.99 tCO_2eq to 7460.15 tCO_2eq for the whole life cycle as 50 years, which means 35.84 tCO_2eq carbon emission reduction for one building.

8.7 Summary

Though all the efforts based on the theoretical research, the proposed new design on one hand, improve the lighting condition for the chosen project; on the other hand, it also reduces the total carbon emission. Therefore, it has strongly shown that reasonable and considerate design can help to achieve a balance quality and environmental impact.

It may only be a single specific project and a minor part of the endless design world, but it shows that even little design changes can make big differences. Apart from that, the field of lighting and carbon emission still has a lot of potential for us to keep digging in the future. It is promising that the design can make a better world and help to achieve a better tomorrow.

BIBLIOGRAPHY

[1] Stevenson F, Isabel C, Hancock M. The usability of control interfaces in low carbon housing[J]. Architecture Science Review, 2013(56):70-81.

[2] Banwell P, Brons J, Rizzo P, et al. A demonstration of energy-efficient lighting in residential new construction[J]. Lighting Research and Technology, 2004(36):147-164.

[3] Acosta I, Campano M, Molina J. Window design in architecture: analysis of energy savings for lighting and visual comfort in residential spaces[J]. Applied Energy, 2016(168):493-506.

[4] Eric S, Jia H, Maulin P. Energy and visual comfort analysis of lighting and daylight control strategies[J]. Building and Environment, 2014(78):155-170.

[5] Edward N. Studies on daylight design and regulation of high density residential housing in Hong Kong[J]. Lighting Research and Technology, 2003(35):127-139.

[6] Zhun Y, Benjamin F, Fariborz H, et al. A systematic procedure to study the influence of occupant behavior on building energy consumption[J]. Energy and Buildings, 2011(43):1409-1417.

[7] Peng X, Mak C, Cheung D. The effects of daylighting and human behavior on luminous comfort in residential buildings: a questionnaire survey[J]. Building and Environment, 2014(81):51-59.

[8] Peter T, Michael W. Daylighting: Architecture and lighting design[M]. Routledge, 2011.

[9] Wood G, Newborough M. Dynamic energy-consumption indicators for domestic appliances: Environment, behaviour and design[J]. Energy and Buildings, 2003(35):821-841.

[10] Helmut K. Dynamic daylight Architecture: Basics, systems, projects[M]. Brikhauser, 2004.

[11] Friedman A. Fundamentals of sustainable dwellings[M]. Island Press, 2012.

[12] Reed B. The integrated design guide to green building: redefining the practice of sustainability[M]. John Wiley & Sons, 2009.

[13] Valentina F, Rune A, Stefano P. A methodology for modelling energy-related human behavior: Application to window opening behavior in residential buildings[J]. Building Simulation, 2013(6):415-427.

[14] Tianzhen H, Sarah C. Taylor L, et al. Advances in research and applications of energy-related occupant behavior in buildings[J]. Energy and Buildings, 2016(116):694-702.

[15] Yujiro H, Tomohiko I, Yukiko Y. Estimating residential CO_2 emissions based on daily activities and consideration of methods to reduce emissions[J]. Building and Environment, 2016(103):1-8.

[16] Simona D, Tianzhen H, William T. An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework [J]. Building and Environment, 2015(92):764-777.

[17] Dong Z, Andrew P, Jing D, et al. Interaction effects of building technology and resident behavior on energy consumption in residential buildings[J]. Energy and Buildings, 2017(134):223-233.

[18] Shan S, Bin Z. Occupants' interactions with windows in 8 residential apartments in Beijing and Nanjing, China[J]. Building Simulation, 2016(9):221-231.

[19] Popoolaa O, Mundaa J, Mpandaa A. Residential lighting load profile modelling[J]. Energy and Buildings, 2015(90):29-40.

[20] Mahlia T, Said M, Masjuki H. Cost-benefit analysis and emission reduction of lighting retrofits in residential sector. Energy and Buildings, 2005(37):573-578.

[21] GB 50176-93 Thermal design code for civil construction.

[22] JGJ 134-2001 Design criteria for energy efficiency of residential buildings in hot summer and cold winter area.

[23] GB 50096-2011 Residential design specifications.

[24] GB 50033-2013 Architectural lighting design standards.

[25] CECS 374-2014 Standard for measuring, accounting and reporting of carbon emission from Buildings.

[26] Chen F, Zhu D. Theoretical methods of low-carbon city research and Shanghai empirical analysis [J]. Urban Development Research, 2009 (10): 71-79.

[27] Sun M. Residential lighting design trends [J]. Residential Science and Technology, 1987 (11): 15-17.

[28] Song Z. Sky conditions in residential lighting design [J]. Residential Science and Technology, 1992 (10): 15-18.

[29] Li D, Zhu M. Discussion on computer simulation of natural light environment for residential design in Beijing [J]. Journal of Illumination Engineering Technology, 2000 (03): 38-43.

[30] Ran M. Determination of minimum window area and window-wall ratio of residential buildings [J]. Journal of Huaqiao University (Natural Science), 2000 (04): 384-389.

[31] Li B. Adaptable to the hot summer and cold winter climate changes in the design of the architectural skin [D]. Tsinghua University, 2004.

[32] Jia D. Bay window with energy-saving housing [J]. China Housing Facilities, 2006 (06): 49.

[33] Jiao Y. Study on energy-saving technology of residential windows in hot summer and cold winter area [D]. Hunan University, 2008.

[34] Chang Z. Changes and utilization strategies of urban residences along the Yangtze River [D]. Chongqing University, 2009.

[35] Zhang B, Li G. Study on design of residential lighting windows based on the concept of lighting energy efficiency [J]. Chinese Journal of Illuminati Engineering, 2010 (4): 14-18.

[36] Xie H. Modern residential and natural lighting [J]. Windows, 2011 (06): 58-61.

[37] Bian W. Analysis of passive house size optimization based on lighting analysis [J]. Journal of Building Energy Efficiency, 2015, (12): 60-63.

[38] Building Energy Conservation Research Center of Tsinghua University. Annual report on China building energy efficiency 2013 [M]. Beijing: China Building Industry Press, 2013.

[39] Ge C, Xiong D. Design and research of natural lighting for modern residential buildings [J]. Residential Technology.2009 (3): 24-27.

[40] Li Z, Jiang Y, Wei Q. Environmental parameters and air conditioning behavior of residential air conditioning energy consumption impact analysis [J]. HVAC, 2007 (8): 67-71.

[41] Li N. Study on the effect of personnel behavior on residential building energy consumption in hot summer and cold winter area [D]. Chongqing University, 2011.

[42] Li Z. Residential human energy behavior and energy consumption of the relationship between the investigation and research in China [D]. Tsinghua University, 2012.

[43] Wang C. Simulation of human behavior on building energy [D]. Tsinghua University, 2014.

[44] Liu X. Building physics [M]. Beijing: China Building Industry Press, 2000.

[45] Maslow A. Motivation and personality [M]. Beijing: Renmin University of China Press, 2007.

[46] Zhu Y. Building environmental science [M]. China Building Industry Press, 2005.

[47] Zhou Y, Hou S. Windows of modern residential buildings [J]. World Architecture, 2004 (10): 80-83.

[48] Jiang Y, Lin B. Residential energy conservation [M]. Beijing: China Building Industry Press, 2006.

[49] Le C. Toward a new architecture [M]. Nanjing: Jiangsu Science and Technology Press, 2014.

[50] Huang G. Energy consumption analysis of residential buildings in hot summer and cold winter zone [D]. Chongqing University, 2006.

[51] Zhang L, Huang Y, Huang X. Carbon evaluation of building life cycle based on standard computing platform [J]. Huazhong Architecture, 2012 (06): 32-34.